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# Lateral Ramps in the Folded Appalachians and in Overthrust Belts Worldwide—A Fundamental Element of Thrust-Belt Architecture

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# Lateral Ramps in the Folded Appalachians and in Overthrust Belts Worldwide—A Fundamental Element of Thrust-Belt Architecture

By Howard A. Pohn

U.S. GEOLOGICAL SURVEY BULLETIN 2163

Lateral ramps in the subsurface can be detected from changes in surface folds. Such changes occur in fold-and-thrust belts worldwide and probably indicate lateral ramps.

**U.S. DEPARTMENT OF THE INTERIOR**
**BRUCE BABBITT, Secretary**

**U.S. GEOLOGICAL SURVEY**
**Charles G. Groat, Director**

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| Multiply | By | To obtain |
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| inch (in) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |

# Lateral Ramps in the Folded Appalachians and in Overthrust Belts Worldwide—A Fundamental Element of Thrust-Belt Architecture

By Howard A. Pohn


## ABSTRACT

Lateral ramps are zones where décollements change stratigraphic level along strike; they differ from frontal ramps, which are zones where décollements change stratigraphic level perpendicular to strike. In the Appalachian Mountains, the surface criteria for recognizing the subsurface presence of lateral ramps include (1) an abrupt change in wavelength or a termination of folds along strike, (2) a conspicuous change in the frequency of mapped faults or disturbed zones (extremely disrupted duplexes) at the surface, (3) long, straight river trends emerging onto the coastal plain or into the Appalachian Plateaus province, (4) major geomorphic discontinuities in the trend of the Blue Ridge province, (5) interruption of Mesozoic basins by cross-strike border faults, and (6) zones of modern and probable ancient seismic activity. Additional features related to lateral ramps include tectonic windows, cross-strike igneous intrusions, areas of giant landslides, and abrupt changes in Paleozoic sedimentation along strike.

Proprietary strike-line seismic-reflection profiles cross three of the lateral ramps that were identified by using the surface criteria. The profiles confirm their presence and show their detailed nature in the subsurface.

Like frontal ramps, lateral ramps are one of two possible consequences of fold-and-thrust-belt tectonics and are common elements in the Appalachian fold-and-thrust belt. A survey of other thrust belts in the United States and elsewhere strongly suggests that lateral ramps at depth can be identified by their surface effects.

Lateral ramps probably are the result of thrust sheet motion caused by continued activation of ancient cratonic fracture systems. Such fractures localized the transform faults along which the continental segments adjusted during episodes of sea-floor spreading.


## INTRODUCTION

The term “lateral ramp” was used by Boyer and Elliott (1982), Butler (1982), and Hossack (1983) to describe a tectonic ramp that is parallel to the transport direction of regional thrust sheets. In this report, the concept of a lateral ramp is expanded to encompass a zone of structural disruption (faulting, folding, and possible intense fracturing) where décollements change stratigraphic level along structural strike.

Although discussions of individual lateral ramps in outcrop and the occasional model of a lateral ramp are not uncommon in the geologic literature, comprehensive discussions of the detailed geometry of lateral ramps and descriptions of these ramps throughout an entire fold-and-thrust belt do not appear to exist. Descriptions of lateral ramps in the southern Appalachians were provided by Thomas and others (1986) and Thomas (1990, 1991).

Because no major thrust fault (frontal ramp or décollement) can continue indefinitely along strike, the presence of lateral ramps in fold-and-thrust belts is the result of one of two possible inevitable occurrences. Thrust faults must either die out by diminishing displacement (fig. 1*A*) or transfer their displacement to some cross-strike fault via a lateral ramp (fig. 1*B*). Close examination of structures in the field and of geologic maps of the central and southern Appalachians shows that large cross-strike faults are not commonly expressed at the surface. Exceptions are rare; they include the Jacksboro fault of the Pine Mountain thrust system (fig. 2) and possibly the Gizzard décollement (present only as scattered klippen on the southern Appalachian Plateaus). However, proprietary seismic-reflection profiles show that large-displacement cross-strike faults are indeed present in the subsurface and form the foundations or deflecting buttresses of lateral ramps. The recognition of surface criteria, indicative of these lateral ramps at depth, is fundamental to an understanding of the structural architecture of the Appalachian fold-and-thrust belt.

Studies by the author in the Appalachian Mountains over the last 17 years have first suggested, then confirmed, a number of surface criteria for recognizing the locations of subsurface or blind lateral ramps. In the Appalachian fold-and-thrust belt, these criteria include (1) an abrupt change in wavelength or a termination of folds along strike, (2) a conspicuous change in frequency of mapped faults or disturbed

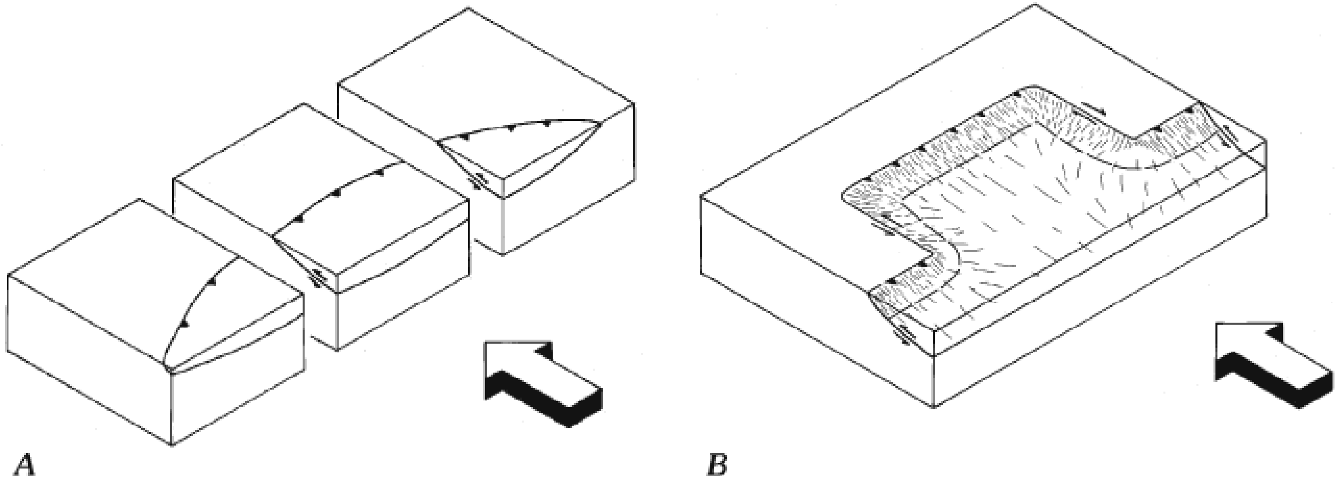



**Figure 1.** Block diagrams of lateral ramps. Small arrows show sense of movement on fault. Full arrow indicates transport direction in block diagrams. *A*, Typical "bow and arrow" structure showing diminishing displacement at the ends of a thrust fault. *B*, Thrust fault with displacement lost to cross-strike faults. Top fault block is transparent.

zones at the surface, (3) long, straight river trends emerging onto the coastal plain or into the Appalachian Plateaus province, (4) major geomorphic discontinuities in the trend of the Blue Ridge province, (5) interruption of Mesozoic basins by cross-strike border faults, and (6) zones of modern and probable ancient seismic activity. Additional features related to lateral ramps include tectonic windows, cross-strike igneous intrusions, areas of giant landslides, and abrupt changes in Paleozoic sedimentation along strike (table 1).

## PURPOSE AND SCOPE

The presence of subsurface frontal ramps (tectonic ramps as defined by Harris and Milici, 1977) parallel to the strike of the Appalachian fold-and-thrust belt has been known since Rich (1934) first proposed such a ramp in his model of the Pine Mountain thrust fault. Since then, others have recognized these frontal ramps at a mesoscopic scale in outcrops and at a megascopic scale (in both seismic-reflection sections and geologic maps at scales as small as 1:1,000,000).

Much less is either known or hypothesized about the nature of transverse structures, although numerous researchers have discussed them or inferred their presence from lineaments on the surface. These features have been called incipient tear faults (Rich, 1934), strike-slip fault-lineaments (Rodgers, 1963), Gwinn-type lineaments (Kowalik and Gold, 1974, after Gwinn, 1964), transverse faults (Harris and Milici, 1977), cross-strike structural discontinuities (CSD's) (Wheeler, 1978), transverse décollements (Kulander and Dean, 1978), and lateral ramps (Boyer and Elliott, 1982; Butler, 1982; Hossack, 1983). Coleman (1988a) briefly discussed the subtle differences among lineaments, CSD's, and lateral ramps.

In general, thrust-belt researchers assumed that these transverse structures are probably strike-slip faults, and that they are a result of tear faulting at the margins of thrust sheets. This report suggests an augmentation of the strike-slip fault hypothesis as illustrated, but not discussed, by Kowalik and Gold (1974); that is, that many of these cross-strike features may be underlain by lateral ramps that serve to transfer décollements from one stratigraphic level to another in the same manner as the frontal ramps, but in a direction normal to the strike of the fold belt. This report further explores the possibility that many of these ramps may have considerable (mile-scale) along-strike movement normal to, or at high angles to, the regional tectonic transport direction.

## ACKNOWLEDGMENTS

The author gratefully acknowledges the generosity of Amoco Production Co., Houston, Tex., which provided the seismic profiles used in this report, and of MARS Associates, Phoenix, Ariz., which provided the radar mosaic image of figure 40. All other radar images were produced as part of a national survey by the U.S. Geological Survey (USGS). All interpretations from these data are by the author.

Finally, I would like to acknowledge the late Terry W. Offield, one of my oldest and closest friends and always my most demanding critic. Terry read and reviewed the manuscript on two separate occasions; although I did not agree with all his comments, the report includes most of them. There is no doubt that the report was improved considerably by his reviews. He will be missed as a reviewer, as a fellow scientist, and as a friend.

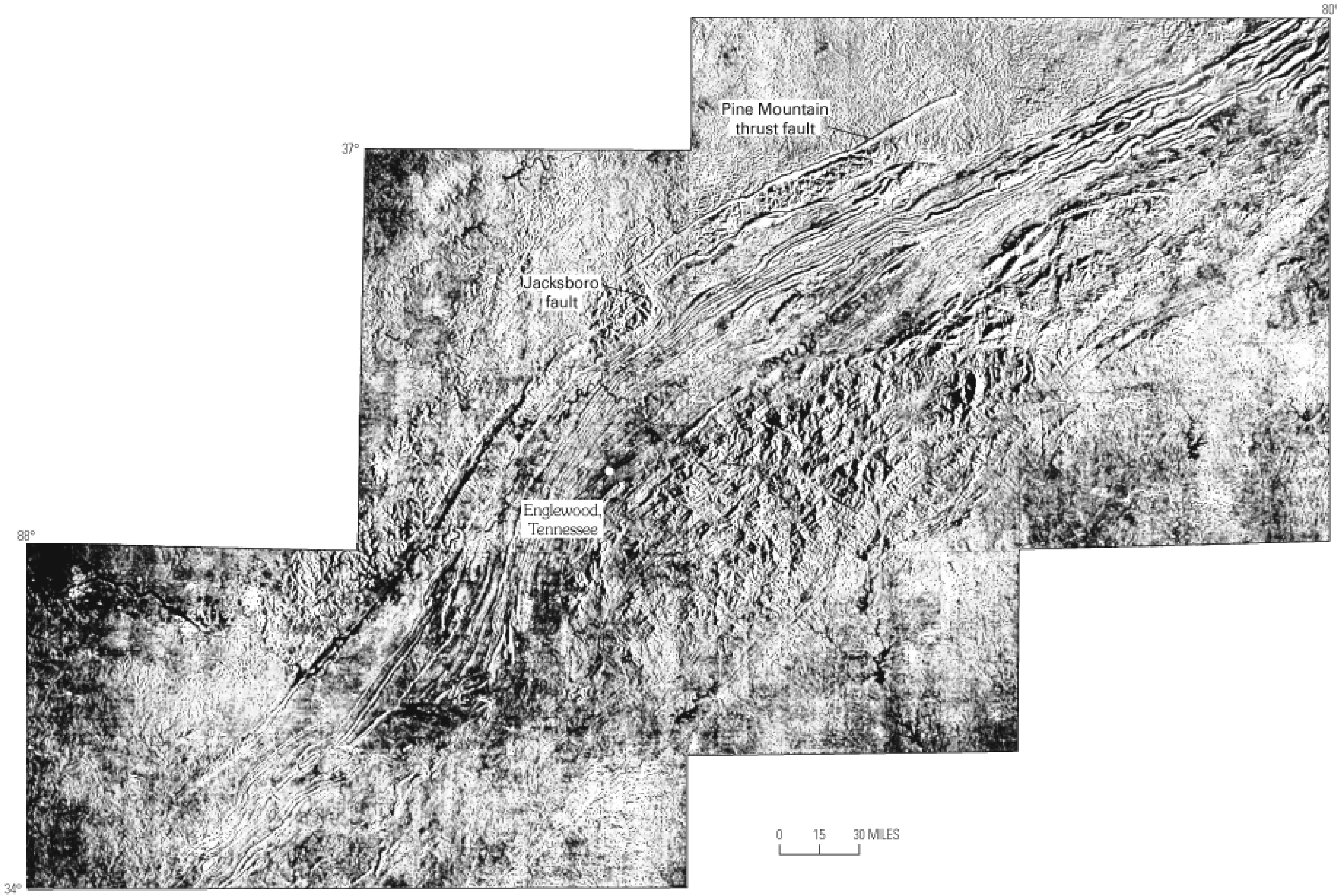



**Figure 2.** Side-looking airborne radar (SLAR) uncontrolled image of the southern Appalachians showing the location of the Jacksboro fault and the Pine Mountain thrust fault in western Tennessee.

**Table 1.** Proposed lateral ramps in the Appalachians and their identifying characteristics.
[X, feature observed; N.O., change in fault frequency not yet observed; dash (—), feature not present; ?, igneous intrusion not certain]

| Proposed lateral ramp name | Abrupt change in fold wavelength | Plungeouts of folds | Straight river trends | Geomorphic discontinuities in Blue Ridge or equivalent | Change in fault frequency at surface | Narrowing, interruption, or termination of Mesozoic basins | Seismic profile evidence |
|---|---|---|---|---|---|---|---|
| Wilkes-Barre | X | X | Susquehanna River-upper reaches of Delaware River. | — | N.O. | — | — |
| Susquehanna | X | X | Susquehanna River | X | X | — | X |
| Seven Mountains | — | X | Middle of Juniata River. | — | X | — | — |
| Tyrone-Mount Union | X | X | Upper reaches of Juniata River. | — | X | — | — |
| Bedford | X | X | — | X | X | — | X |
| Pennsylvania-Maryland-West Virginia | X | X | Patuxent River | X | X | X | X |
| Mathias | X | X | Rappahannock River | X | X | X | X |
| Highland County | — | X | James River | X | X | X | X |
| Lexington | X | X | Upper reaches of James River. | X | X | X | — |
| Roanoke | X | X | Roanoke River and northwest arm of Smith Mountain Lake. | X | X | X | — |
| Blacksburg | — | X | — | — | X | — | — |
| New River | — | X | New River | X | X | X | — |
| Pulaski | — | X | — | — | X | — | — |
| Johnson City | — | X | — | X | X | X | — |
| Kingsport | — | X | — | X | X | X | — |
| Knoxville | X | X | — | X | N.O. | — | — |
| Fontana Lake | — | X | Tennessee River | X | N.O. | — | — |
| Rising Fawn* | — | X | — | — | N.O. | — | — |
| Calhoun | — | X | — | X | N.O. | — | — |
| Springville | — | X | — | — | N.O. | — | — |
| Piedmont | — | X | — | — | N.O. | — | — |

*Previously named by Thomas and Neathery (1980).

# GEOMETRIC CONSIDERATIONS OF LATERAL RAMPS

## OVERVIEW

Simplified models of the geometry of lateral ramps show that four basic configurations are possible (fig. 3*A*–*D*). From the simplest to the most complex, these are parallel-sided ramps connected to a horizontal décollement (fig. 3*A*), parallel-sided ramps connected to a rising décollement (fig. 3*B*), convergent-sided ramps connected to a horizontal décollement (fig. 3*C*), and convergent-sided ramps connected to a rising décollement (fig. 3*D*).

Each of these geometries, with the exception of the first, produces a smaller cross-sectional area at its distal end than at its proximal end. Thus, each of these last three geometries requires some lateral spillover, or movement along strike, of the compressed materials. Note that none of these last three examples requires the presence of a frontal ramp to initiate movement along strike. The lateral movement is produced entirely by volumetric constriction in the direction of tectonic transport. Even the parallel-sided ramp connected to a horizontal décollement may produce movement along strike if the angle on the lateral ramp is shallower than the dip of an accompanying frontal ramp or if the materials along strike are more compressible than are the materials along dip.

Note that the last two examples produce a paradox in terminology. Both are more correctly considered to be oblique ramps rather than lateral ramps at depth, but the surface manifestation of these oblique ramps shows the geometry of true lateral ramps. Conversely, a slightly different geometry of the spillover of materials might make true lateral ramps at depth appear to be oblique ramps at the surface.

Furthermore, the question arises as to what amount of obliquity is permitted before a lateral ramp should be termed an oblique ramp. If one degree of obliquity (deviation from parallelism to the transport direction) is sufficient to change the term from lateral to oblique, then there is no such thing as a lateral ramp. Clearly, in order to truly define lateral and oblique ramps, one must have the benefit of three-dimensional seismic-reflection profiles, because only then can the worker determine the geometries of both the surface and subsurface. In this report, because the author does not have access to three-dimensional seismic-reflection profiles, and therefore cannot determine the geometries from subsurface to surface, all of the examples are considered to be lateral ramps.

**Table 1.** Proposed lateral ramps in the Appalachians and their identifying characteristics—Continued.

| Proposed lateral ramp name | Modern earthquakes (1628 to present) | Giant landslides (Schultz and Southworth, 1989) | Tectonic windows | Abrupt change in thickness of facies | Coarse pebble conglomerates | Igneous intrusions | Major lineaments crossing Precambrian block | High frequency of mineral deposits | Geophysical evidence |
|---|---|---|---|---|---|---|---|---|---|
| Wilkes-Barre.................... | X (9) | — | X | X | X | — | — | — | — |
| Susquehanna..................... | X (11) | — | X | X | X | X | — | X | — |
| Seven Mountains............. | — | X | — | — | — | — | — | — | — |
| Tyrone-Mount Union....... | X (2) | — | X | — | — | — | — | — | X |
| Bedford............................ | — | — | — | X | — | — | — | — | X |
| Pennsylvania-Maryland-West Virginia................ | X (5) | X | — | X | X | X | — | — | — |
| Mathias............................ | X (7) | — | — | X | — | ? | — | X | — |
| Highland County............ | X (22) | — | — | — | — | X | — | — | X |
| Lexington......................... | X (1) | — | — | — | — | — | — | — | — |
| Roanoke........................... | X (5) | X | X | X | X | — | — | — | X |
| Blacksburg....................... | X (6) | X | X | — | — | — | — | — | — |
| New River........................ | X (7) | X | X | X | — | X | — | — | — |
| Pulaski............................. | X (11) | X | X | — | X | — | — | — | — |
| Johnson City................... | X (11) | — | X | — | — | X | — | — | — |
| Kingsport......................... | X (10) | X | X | — | — | — | X | — | — |
| Knoxville.......................... | X (17) | — | X | — | — | — | — | — | — |
| Fontana Lake.................... | X (7) | — | X | — | — | — | — | — | — |
| Rising Fawn*................... | X (10) | — | X | X | — | X | — | X | X |
| Calhoun............................ | X (8) | — | X | — | — | — | X | — | — |
| Springville........................ | X (3) | — | X | — | — | — | — | — | — |
| Piedmont.......................... | X (7) | — | X | — | — | — | X | — | — |

## THE BASIC MODEL

The basic model of lateral ramps assumes that two phenomena are true. The first is that structures in the Appalachians are, for the most part, scale independent (Rogers, 1858; Nickelsen, 1963; Faill, 1973; Pohn and Purdy, 1982, 1988; Pohn and Coleman, 1991). Thus, if a particular structure occurs in outcrop, it probably also occurs at other scales, such as in thin section, at quadrangle-mapping scale, or at seismic-reflection-profile scale. Scale independence is important because the perception and thorough understanding of a lateral ramp at outcrop scale can yield important clues for the detailed structural interpretation of lateral ramps on seismic-reflection profiles.

Figure 4*A* is a sketch of an example of a complex ramp anticline structure in the central Appalachian Valley and Ridge province. The first question that comes to mind is, "What is the scale of the example?" There are two answers to this question. The first is that this example is a hand specimen about 5 in long. The second answer is, "it probably doesn't matter," because this exposure could be 1 or 10 in long, or 1 or 10 mi long. In fact, figure 4*B* shows another sketch of a quite similar ramp anticline, but this is from a seismic-reflection profile in the central Appalachian Valley and Ridge province, and the anticline's long dimension is approximately 6 mi. Figures 4*C* and 4*D* show a photograph of the hand specimen example and the seismic record. The same types of features were seen in thin sections, outcrops, and seismic-reflection profiles over at least eight orders of magnitude (0.1 in to 10 mi) and may exist at least an order of magnitude both smaller and larger. This qualitative observation indicates that these geologic patterns are scale independent and, therefore, fractal (Christopher Barton, USGS, oral commun., 1992).

The second phenomenon, which can also be confirmed in the field, is that faults are contemporaneous with or predate the associated folds. Field observations show that in the Valley and Ridge and Appalachian Plateaus provinces of the Appalachians, either anticlines in the hanging walls or synclines in the footwalls of faults are usually present. However, the occurrence of both anticlines and synclines of the same approximate magnitude and associated with the same fault is rare. Seventeen years of mapping structures in the Valley and Ridge and Appalachian Plateaus provinces has revealed only two anticline-syncline pairs that were related to the same fault. If the folds preceded the faults, then observations should show an anticline in the hanging wall and a syncline in the footwall of virtually every thrust fault, but this was not observed. Therefore, faults must precede or be contemporaneous with their associated folds.

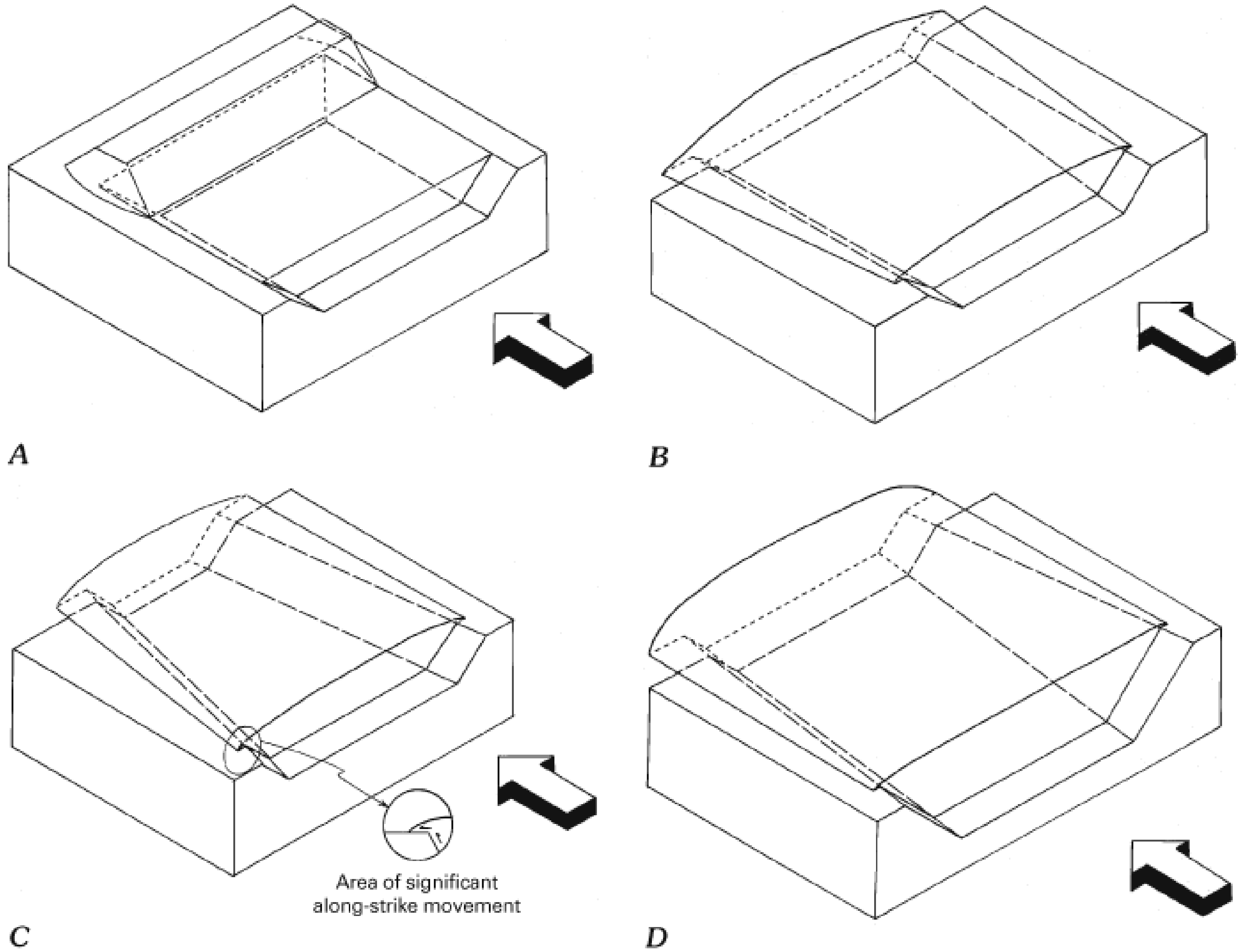



**Figure 3.** Simplified block diagrams of lateral ramps showing four basic geometric configurations. Arrows show sense of movement on fault. *A*, Parallel-sided lateral ramp connected to a horizontal décollement. *B*, Parallel-sided lateral ramp connected to a rising décollement. *C*, Convergent-sided lateral ramp connected to a horizontal décollement. *D*, Convergent-sided lateral ramp connected to a rising décollement.

In addition, if folds preceded faults, then one ought to see similar wavelengths of folds when a train of folds is interrupted by large-displacement faults. Instead, what is usually observed is a considerable change in wavelength of folds as each large displacement discontinuity is crossed. This observation also seems to indicate that faults must precede or be contemporaneous with the associated folds (Pohn and Purdy, 1982).

From these observations and interpretations, several inferences may be made: (1) the spacing between thrust faults controls the wavelength of included folds; wide spacing between thrust faults gives rise to broad folds, and narrow spacing gives rise to small folds; and (2) as shown in figure 5, the spacing of faults, in turn, is controlled by the position of the fault above the décollement. Splay faults are listric; that is, curvilinear, concave-upward surfaces to which the master décollement is tangent. Seismic and outcrop data show that fewer secondary and tertiary faults branch off the lower order splay faults at depth (nearer the décollement) than at distances farther from the décollement. Many of these faults die out as blind thrusts (Boyer and Elliot, 1982; Butler, 1982). The convergence of higher order splay faults causes the spacing between thrust faults nearer the décollement to be wider than the spacing between the faults at greater distances above the décollement (fig. 5).

Jacobeen and Kanes (1974, 1975) presented evidence for the concept that many frontal ramps overlie areas of basement block faulting in the folded Appalachians. They suggested that these ramps exist because of the crowding of beds against the block fault in response to compressional stresses resulting from Alleghanian plate convergence; these stresses, in turn, force bedding-plane faults (décollements) to ramp upward to a higher stratigraphic level. Figure 6 shows dip-line seismic data illustrating just such a situation in northeastern West Virginia. This profile supports the fault interpretation of Jacobeen and Kanes (1974, 1975).

If basement block faults parallel to the structural strike of the Valley and Ridge province lead to the formation of frontal ramps, then block offsets on basement faults perpendicular or nearly perpendicular to the strike of the Valley and Ridge province might similarly give rise to the formation of a lateral ramp (fig. 7). If a basement block fault is present at even a slight angle to the maximum principal stress direction of the orogenic movement, the compressive forces cause the rocks adjacent to basement to be refracted up the fault face, and thus produce an environment favorable to the formation of a lateral ramp. In addition, the steepness of the fault scarp controls the amount of refraction of the superjacent beds. Steep fault scarps generally refract steeply, whereas gently dipping fault scarps refract at gentler angles (fig. 8).

# FIELD EXAMPLES AND SUPPORTING DATA

## SUSQUEHANNA LATERAL RAMP

In the anthracite belt of central Pennsylvania, an obvious discontinuity exists between the wavelength of folds generally to the east of the Susquehanna River and the wavelength of folds generally to the west of the river (fig. 9). Only the Montour anticline (figs. 10 and 11) persists as a significant positive structural element across the river, and even this anticline is slightly offset. The change in fold wavelength is undoubtedly partially related to a ductility contrast in lithotectonic units (Currie and others, 1962; Nickelsen, 1963; Wood and Bergin, 1970); however, some of the discrepancy is related to the presence of a lateral ramp that underlies the Susquehanna River. Supporting evidence is given below.

Solely on the basis of seismic expression, Pohn and Coleman (1991) interpreted seismic basement as a gently undulate surface that rises from a total depth of 47,000 ft southwest of the river to 26,250 ft northwest of the river. Conversely, seismic basement rises from a total depth of 42,000 ft southeast of the river to 35,000 ft northeast of the river. This type of dip reversal indicates the presence of basement slopes in a scissors fault with the inflection (hinge) below the Montour anticline (fig. 10). The steeper gradient to the north and west of the river and the maximum slope on the basement, which is at a slight angle to the tectonic transport direction, produce an environment favorable for the formation of a lateral ramp (fig. 10).

### STRATIGRAPHIC AND STRUCTURAL SETTING

The area of the Susquehanna lateral ramp is underlain by a combination of Paleozoic carbonate rocks, siltstones, and shales with minor sandstones (Berg, 1980; Berg and Dodge, 1981). Much of this stratigraphic section (fig. 12) was penetrated by the Amoco No. 1 Wilhour Gas Unit well, which is 14,737 ft deep and located near the crest of the Shade Mountain anticline (fig. 11). This well yielded considerable valuable stratigraphic and structural information, although it did not penetrate the thrust fault that appears to core the anticline, according to the seismic-reflection profile (fig. 13). This thrust fault lies approximately 5,380 ft below the bottom of the well.

Shales and siltstones of the Middle Devonian Hamilton Group crop out at the well location. A normal stratigraphic section of Devonian to Lower Ordovician strata was encountered throughout the first 11,440 ft in the well. At this depth, the well crossed a reverse fault and repeated the lower 1,070 ft of the section present in the hanging wall. Dolostones of the Lower and Middle Ordovician Beekmantown Group, and possibly the Upper Cambrian Gatesburg Formation, are present in the footwall, where they either are intensely folded or dip to the south at angles of 40° to 70°.

In addition to the stratigraphic classification, the rock assemblages in the well have been grouped into lithotectonic units, each of which exhibits a distinctive structural geometry (fig. 12). Five of the units are described below:

Unit I. Shales of the Hamilton Group (unit I) behave as a ductile mass and exhibit disharmonic folding, but their shallow depth of burial reduces their contribution to the overall structural complexity.

Unit II. The interval from the top of the Devonian Onondaga Limestone to the base of the Silurian Tonoloway Formation is unit II, which is a more competent sequence than unit I.

Unit III. Beneath the Tonoloway Formation is unit III, a 1,820-ft-thick (estimated true thickness) relatively incompetent section of silty and (or) sandy shales, including the Silurian Wills Creek Formation, Bloomsburg Red Beds, and Rose Hill Formation, which display generally southerly dips ranging from 8° to 25°.

Unit IV. Beneath the Rose Hill Formation is unit IV, which is more competent (and more harmonically folded) than unit III; unit IV is a sequence of medium- to thick-bedded sandstones of the Lower Silurian Tuscarora Formation and the uppermost part of the Upper Ordovician Juniata Formation.

Unit V. Underlying unit IV is unit V, which is an approximately 3,490-ft-thick interval of silty and sandy shale and sandstone of the lower part of the Juniata Formation and the Bald Eagle Formation and shales of the Upper Ordovician Reedsville Shale.

Map patterns on the geologic map of Pennsylvania (Berg, 1980) suggest that little disharmonic folding occurs below unit III other than in the Reedsville Shale and near the

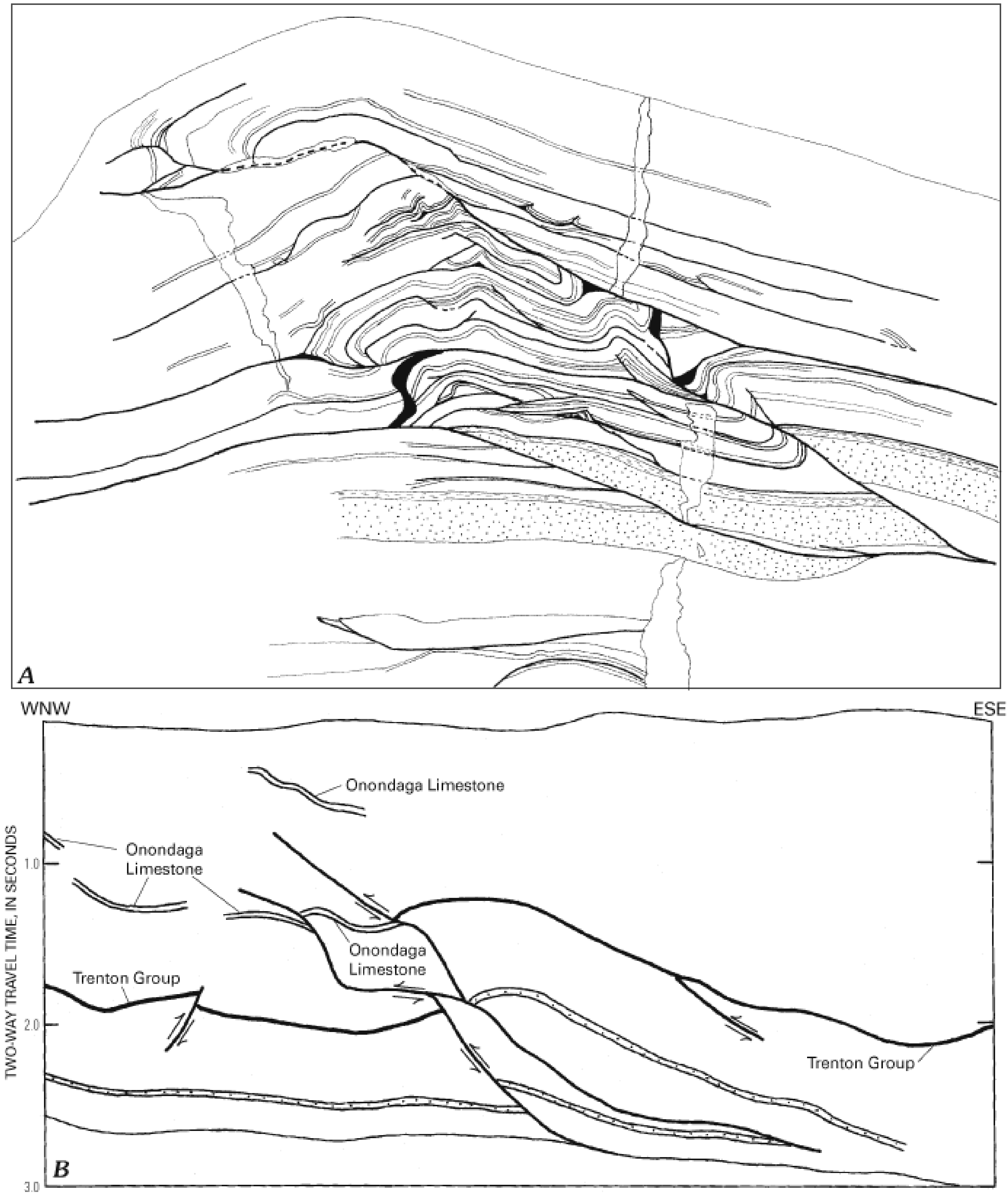



**Figure 4.(above and facing page).** Illustration of the scale of folds, faults, and ramps. *A*, Sketch of hand specimen photographed for figure 4*C*, from the central Appalachian Valley and Ridge province. *B*, Sketch of seismic-reflection profile of figure 4*D*, from the Appalachian Valley and Ridge province. Arrows show sense of movement of faults. *C*, Photograph of the hand specimen sketched in figure 4*A*, from the Brallier Formation near Moorefield, W. Va. Specimen is about 5 in across. *D*, Seismic-reflection profile of the West Virginia Valley and Ridge province section sketched in figure 4*B*. Arrows show sense of movement along faults. Profile shows seismic data collected along a line approximately 21 mi long.

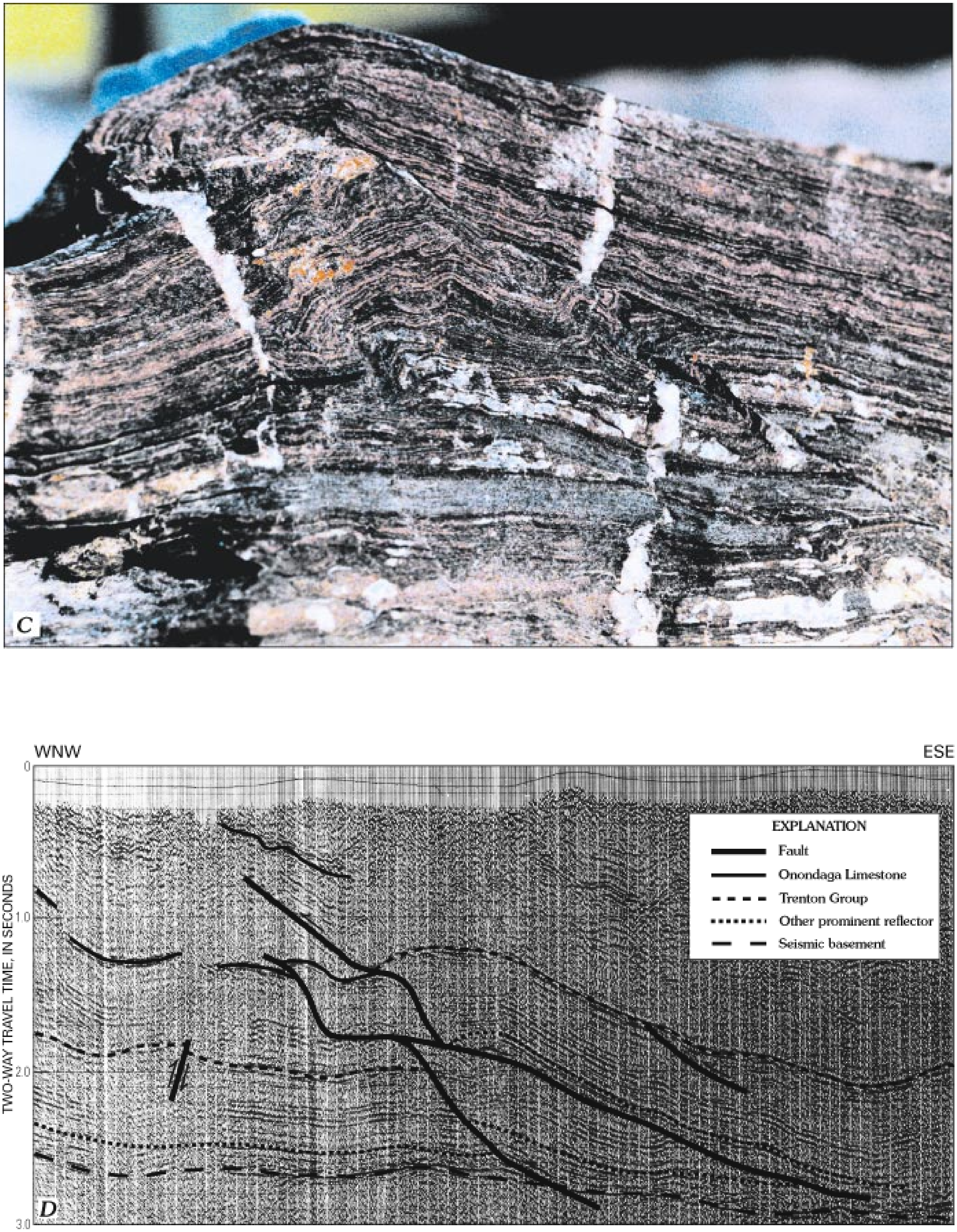



**Figure 4.** Continued.

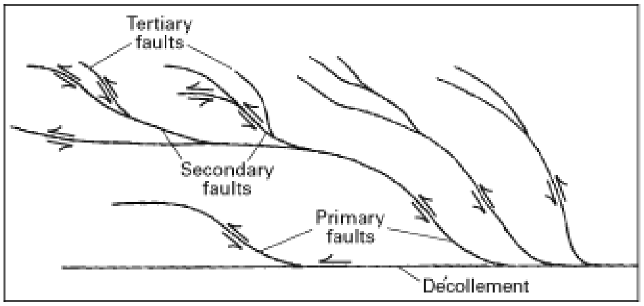



**Figure 5.** Sketch showing the relationship of a décollement to primary, secondary, and tertiary faults. Arrows show sense of movement on faults.

basement, where the basal thrust fault produces the major displacement in the region.

Seismic-reflection profiles show key reflectors that are approximately coincident with the Onondaga Limestone, the carbonate rocks at the top of the Trenton Group, and the Precambrian basement (figs. 14, 15). The seismic expression indicates that the Precambrian basement rises from a depth of approximately 35,000 ft in the southeast to a depth of about 26,250 ft in the northwest. This change in elevation of approximately 8,750 ft is almost identical to the relative elevation change of 8,950 ft expressed by the stratigraphic interval encompassing the Hamilton to Beekmantown Groups west of the Susquehanna River.

## SEISMIC EVIDENCE

Two seismic lines were used to evaluate the nature of the lateral ramp that underlies the Susquehanna River. One is a dip line (fig. 14), and one is a strike line (fig. 15). Three key reflectors are present on these lines and, indeed, are present on most seismic-reflection profiles in Pennsylvania. These reflectors roughly correspond to the Middle Devonian Onondaga Limestone, the carbonate rocks at the top of the Middle Ordovician Trenton Group, and the top of Precambrian basement.

### DIP-LINE SECTION

Several significant features can be seen on the dip line (fig. 14). Perhaps the most distinctive feature on this line is the disharmonic folding that occurs just below the Onondaga Limestone. The décollement below the Onondaga Limestone is located within the Silurian Wills Creek Formation. Field observations confirm that the Wills Creek Formation gives rise to décollements in central Pennsylvania. In figure 14, the décollement appears to behead the small anticline at the left-hand (north) side of the seismic-reflection profile. This same feature appears on other proprietary seismic-reflection profiles along strike. The beheaded part of this anticline should appear in the hanging wall of the décollement somewhere to the north of the section shown in figure 13; significantly, however, in proprietary lines north of and parallel to this line, no anticlinal tops are present above the décollement. The absence strongly implies that the top of the anticline has been transported onto the Appalachian Plateaus beyond the limit of the available data. The distance of this transport is a minimum of 20 mi.

Figure 14 and adjacent parallel proprietary seismic-reflection profiles are excellent examples of downplunge projection (Mackin, 1950). Each anticline in the carbonate rocks at the top of the Trenton Group can be traced westward more than 30 mi to the folds that crop out west of the Susquehanna River. The broad Milton anticline at the level of the Onondaga Limestone also can be traced to the surface.

In figure 14, the first syncline adjacent to the Milton anticline at the level of the Onondaga Limestone is the southwesternmost tip of the Lackawanna syncline. In the center of the profile, the zone that shows few or no reflections is the Montour anticline (also known as the Berwick anticline). The paucity of reflectors on this structure is due to limb dips that exceed 45°. The axis and south limb of the Northumberland syncline can be seen at the right center of the profile. The southernmost feature seen on the profile is the Shade Mountain anticline. Note that both the Shade Mountain and Milton anticlines are antiformal stacks as defined by Boyer and Elliott (1982). A close examination of the smaller anticlines under the Milton anticline reveals that they, too, are small antiformal stacks. These structures within structures reinforce the concept that most structures in the Appalachians (and, indeed, in compressional tectonic regimes anywhere) are probably scale independent (Rogers, 1858; Nickelsen, 1963; Faill, 1973; Pohn and Purdy, 1982; Pohn and Coleman, 1991).

The sequence of events leading to the present structural configuration appears to be as follows:

1. The first structures that formed must have been the smaller anticlines presently seen under the Milton anticline.
2. The tops of these anticlines were beheaded by the thrust fault that transported the anticlinal tops out onto the Appalachian Plateaus. No major structures existed to the south of the smaller anticlines, because, if such structures were present, then they would show up in the hanging wall of the décollement at the level of the Wills Creek Formation. Similarly, if the décollement formed before the small anticlines, then the décollement would be folded conformably with the small anticlines.
3. Finally, the Milton, Montour, and Shade Mountain anticlines were formed. Note that the broad arch of the Milton anticline is mirrored by the broad arch that can be drawn through the bases of the small anticlines subjacent to the Milton anticline.

#### STRIKE-LINE SECTION

A strike-line section very nearly perpendicular to the dip-line section of figure 14 is shown in figure 15. The uppermost major reflector at the level of the Onondaga Limestone appears to be plunging gently to the east. Slightly below this reflector, the décollement in the Wills Creek Formation is weakly apparent. Still lower, an unusual “porpoising” is apparent in the reflectors that correlate with the top of the carbonate rocks of the Trenton Group. These “porpoising” features are apparently anticlinal crests that have been truncated and translated westward by a middle-level fault below the top of the Trenton Group. Translation of these Trenton Group crests both northward along synthetic thrust faults and westward along the same fault indicates either two nearly orthogonal directions of thrusting or two components of a single movement. The disharmony between the crests and the relatively flat décollement show that the Trenton Group crests were formed first by northward-directed thrusting. As translation proceeded northward, constriction of the overlying sedimentary sequence by a gradually westward-rising basement forced this displacement to take a westward component. Continued constriction by the mass of the sedimentary pile and the anisotropy of the disharmonically folded Silurian shales forced the rupture of the otherwise coherent carbonate anticlinal crests, sheared them off, and transported them 3 to 4 mi to the west.

Below this décollement and approximately one-third to one-half the distance to seismic basement, two additional faults can be seen cutting the section upward to the west. These two lower thrust faults taken together constitute the primary zones of dislocation along the Susquehanna lateral ramp.

Additional information and a more thorough discussion on the Susquehanna lateral ramp can be found in Pohn and Coleman (1991).

## PENNSYLVANIA-MARYLAND-WEST VIRGINIA LATERAL RAMP

The presence of a broad lateral ramp, rising to the south, in the region where the borders of Pennsylvania, Maryland, and West Virginia join is strongly indicated from field work, radar data, and proprietary seismic data. This ramp, which strikes N. 60° W., appears to be bounded on the north and south by the relatively straight segments of the Potomac River southwest of Hancock, Md. (fig. 16).

North of this area, major folds in the Valley and Ridge province are relatively broad and range from 2 to 11 mi in width. South of the area, the folds are relatively narrow and range from 0.25 to 5 mi in width. The surface and subsurface expressions of the ramp include more than just a change in fold wavelength. Four lines of evidence are described below:

1. Field mapping of disturbed zones shows that the frequency, length, and concentration of such zones increase abruptly and conspicuously to the south of the Pennsylvania-Maryland-West Virginia State line juncture. The disturbed zones are long, narrow zones of intensely thrust-faulted and folded rocks intercalated in otherwise relatively undeformed sections and represent the surface manifestations of splay faults (Pohn and Purdy, 1982, 1988). This increase in disturbed zones is accompanied by an equally abrupt decrease in fold wavelength south of the line. The increase in faulting and decrease in fold wavelength indicate that the master décollement is closer to the surface south of the juncture.
2. Proprietary seismic data show a cross-strike basement extensional fault down-to-the-north accompanied by an abrupt shallowing of reflectors to the south of the juncture.
3. Seismic data from the Appalachian Plateaus show the master décollement to be deeper to the north of the Pennsylvania-Maryland-West Virginia ramp (James Farley, petroleum consultant, oral commun., 1983).
4. The Appalachian structural front conspicuously shifts eastward south of the Pennsylvania-Maryland-West Virginia juncture, which would be expected if the décollement was shallower to the south (fig. 17).

## MATHIAS LATERAL RAMP

#### SURFACE EVIDENCE

A lateral ramp in the area of Mathias, W. Va., is suggested because of a number of fold plunges and changes in fold wavelength across the Valley and Ridge province and because of the generally straight course of the Rappahannock River as it crosses the coastal plain. Field investigations revealed an unusually high frequency of disturbed zones as well as a small up-to-the-north lateral ramp exposure north of Mathias.

A strike-line seismic-reflection profile (fig. 18) shows that there is a lateral ramp in the suspected area and that the ramp appears to rise more than 6,000 ft from north to south. Most of this rise is lost at the southern edge of the ramp as the lateral spillover decreases (see above section “Geometric Considerations of Lateral Ramps” for the explanation of this loss). An additional surface manifestation of the deep-seated Mathias lateral ramp is reflected in the coastal plain where the Rappahannock River trends almost straight southeastward along the northern border of the ramp.

#### SEISMIC EVIDENCE

The Mathias ramp is by far the most complex of the lateral ramps seen in seismic-reflection profiles. At the north

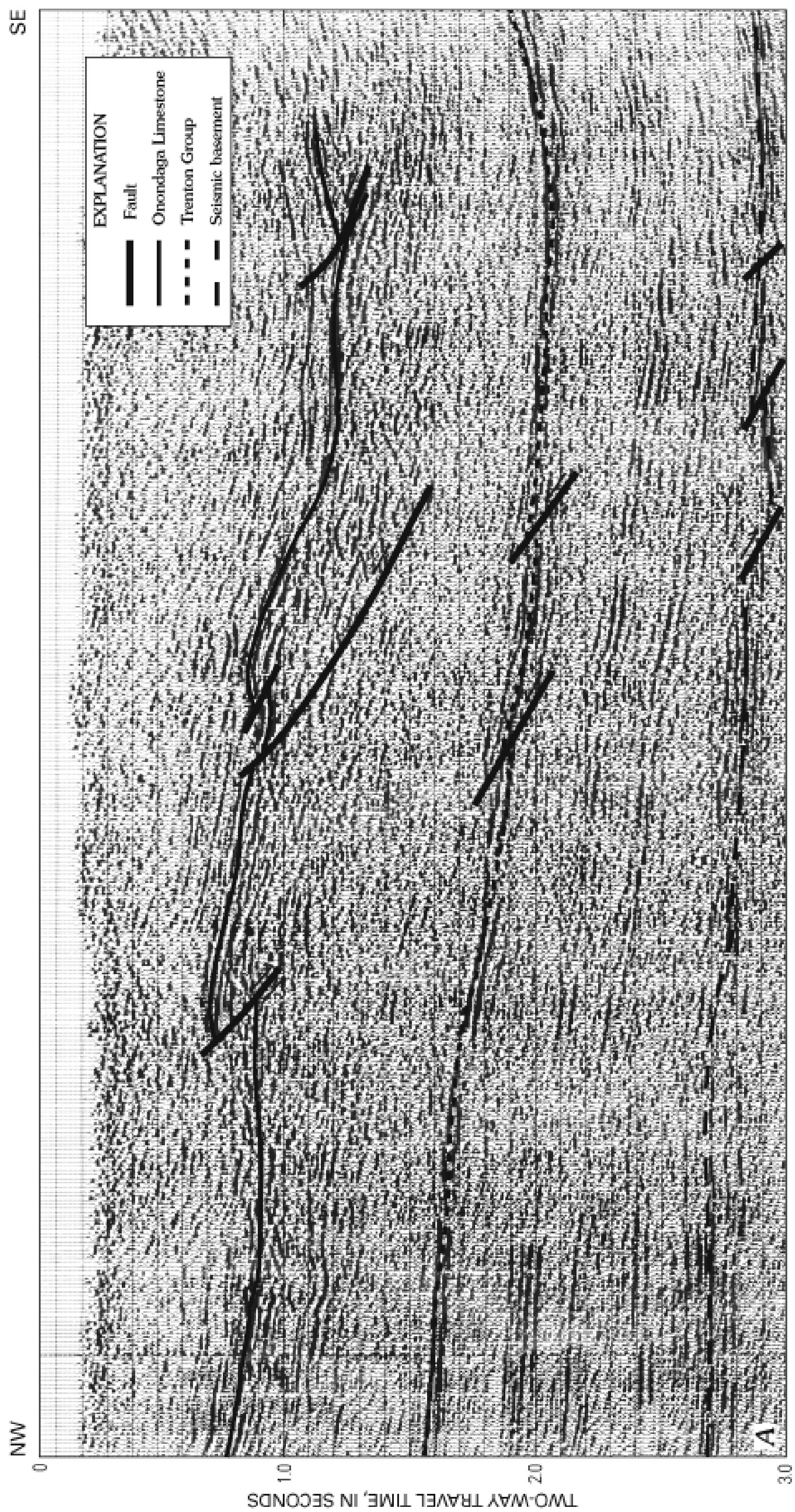



**Figure 6 (above and facing page).** *A*, Dip-line seismic-reflection profile in northeastern West Virginia showing the relationship of tectonic ramps to basement block faults. Arrows show sense of movement in faults. Profile shows seismic data collected along a line approximately 9 mi long. *B*, Same profile as *A* but uninterpreted.

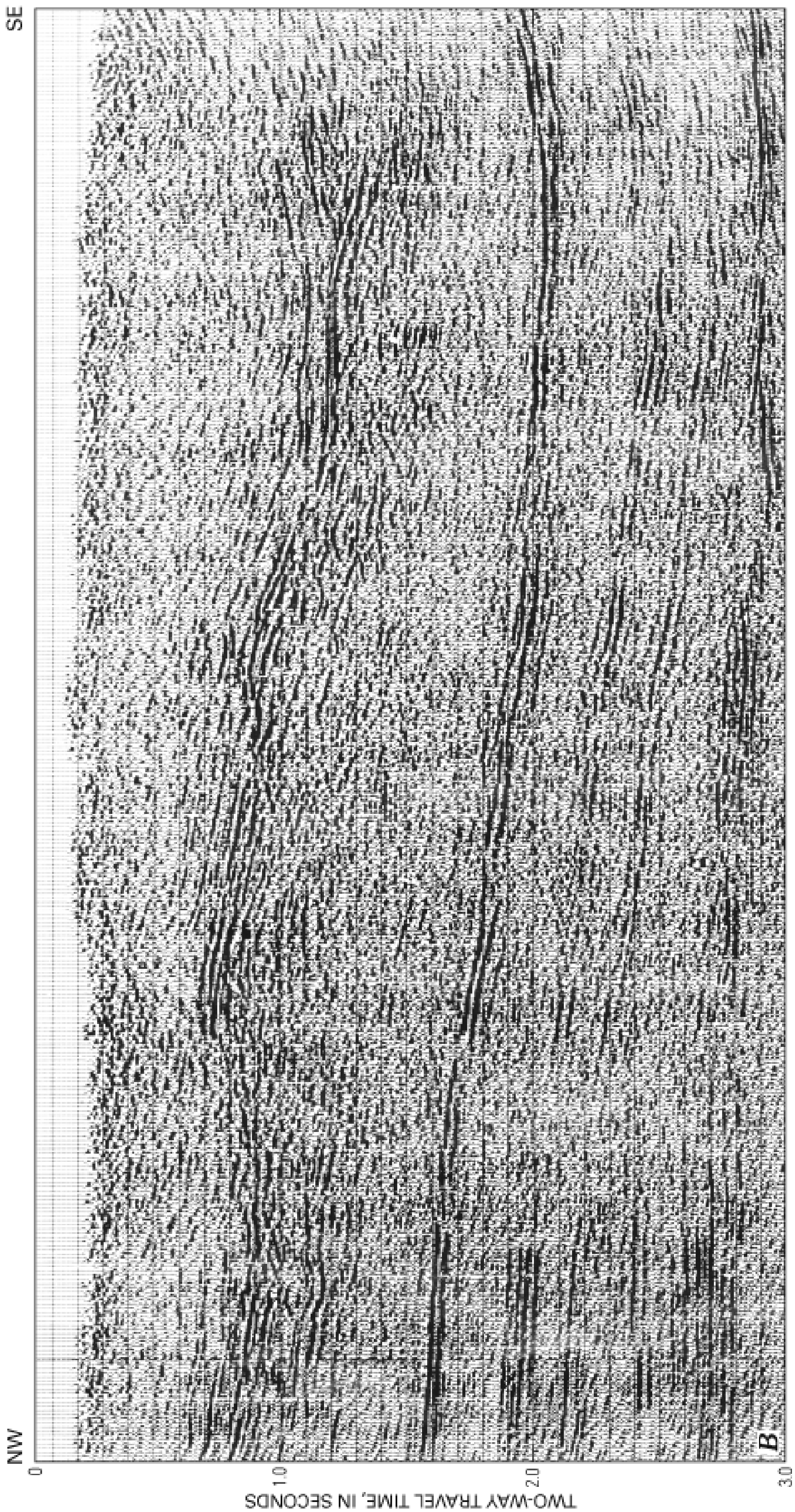



**Figure 6.** Continued.

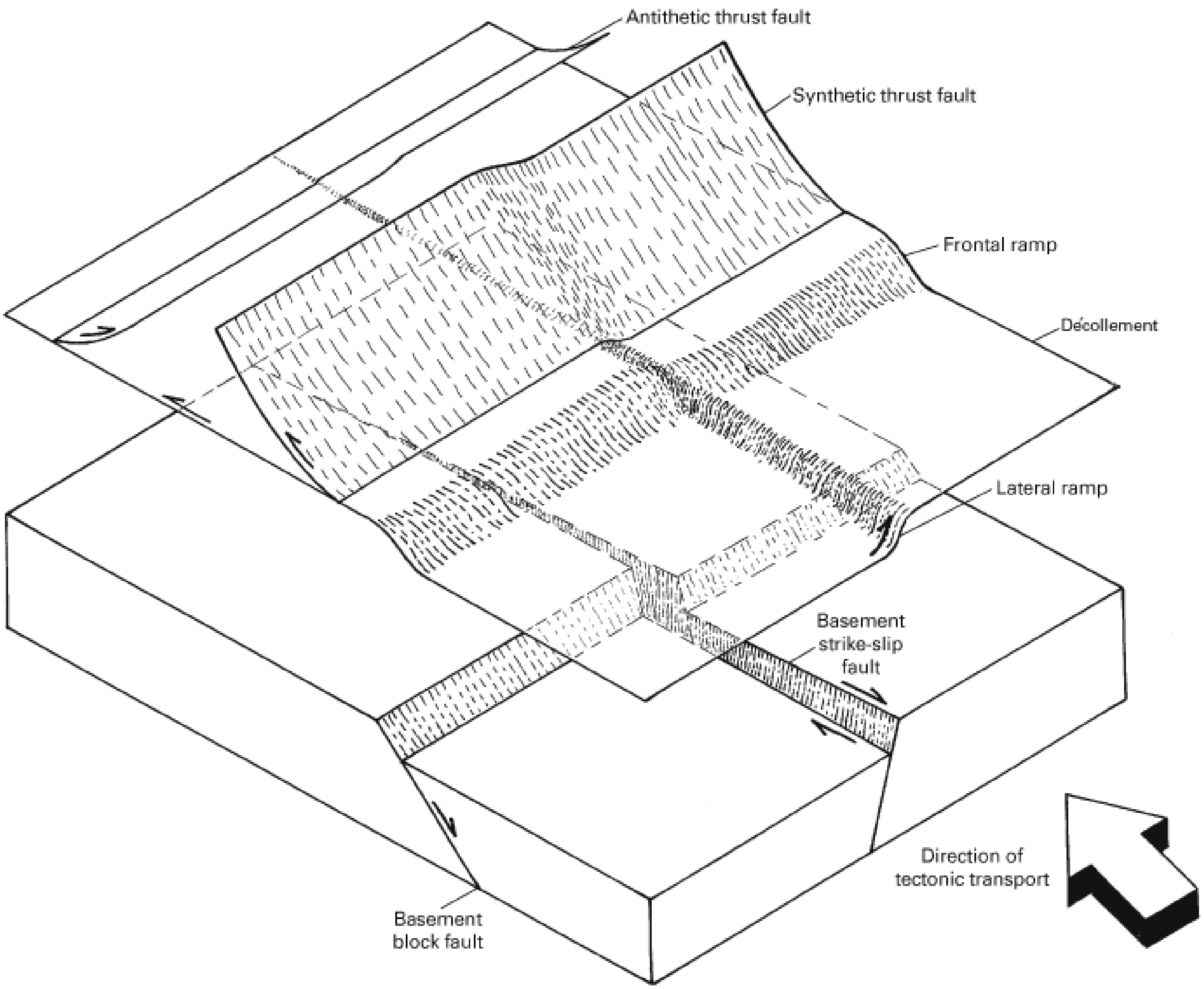



**Figure 7.** Block diagram showing relationship between basement block faults and frontal ramps and between basement cross-strike faults and lateral ramps (from Pohn and others, 1985). Arrows indicate relative movement.

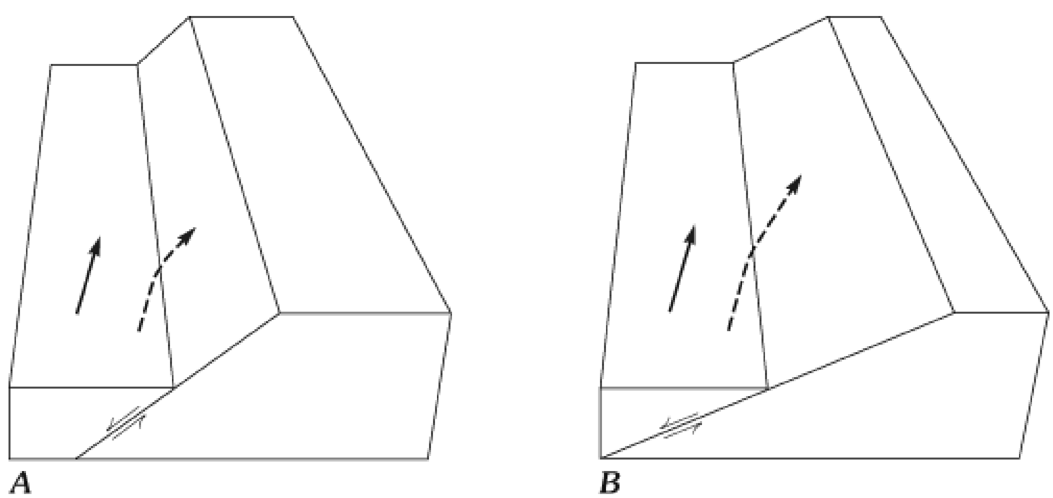



**Figure 8.** Block diagrams showing relationship of fault refraction to steepness of fault scarp. *A*, Steep faults refract steeply. *B*, Shallow faults refract shallowly.

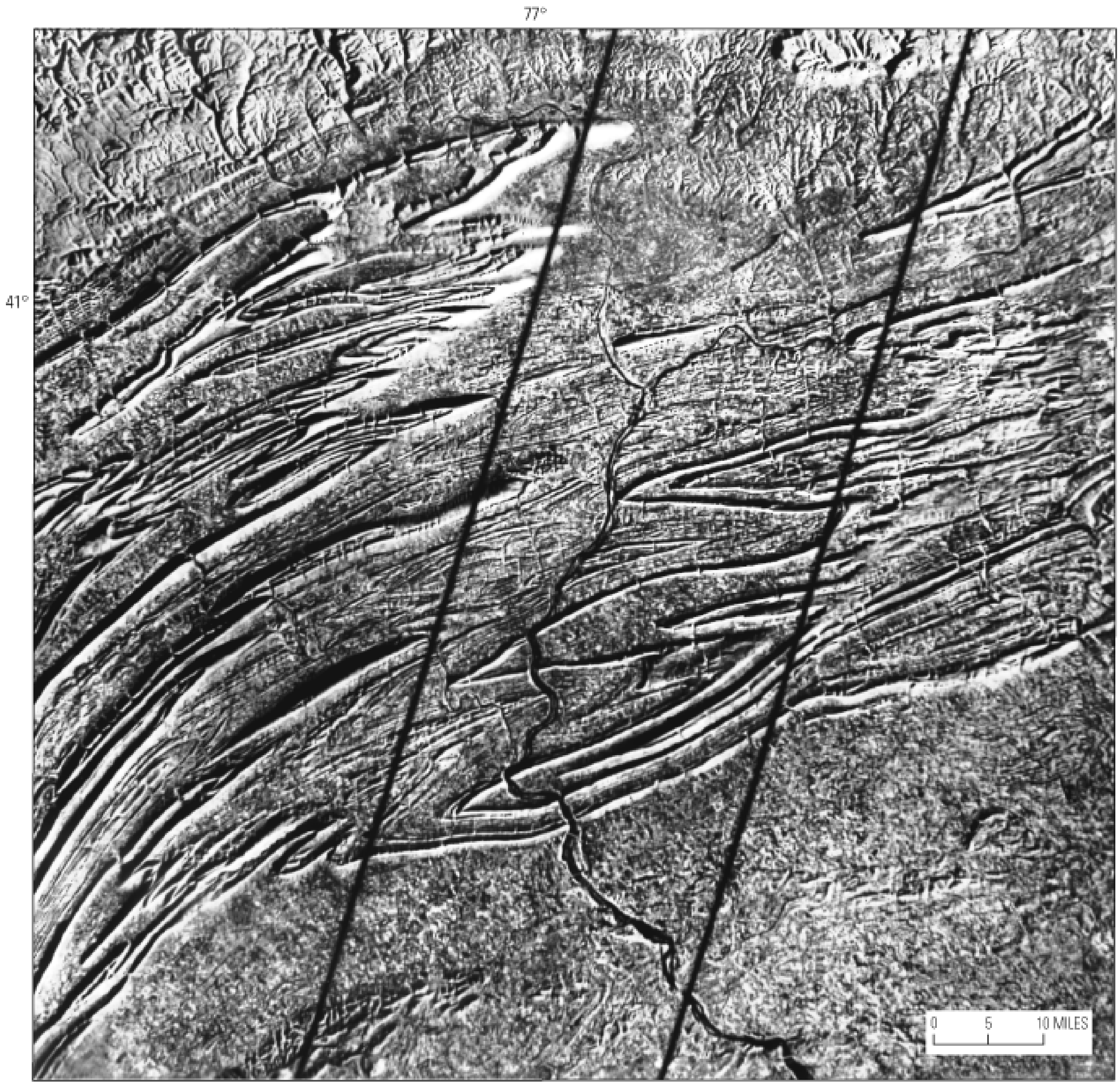



**Figure 9.** Side-looking airborne radar (SLAR) image of the southern part of the Williamsport 1°×2° quadrangle and the northern part of the Harrisburg 1°×2° quadrangle, central Pennsylvania, showing broad folds of the anthracite district east of the Susquehanna River and narrower folds west of the river. Heavy straight lines indicate boundaries of the Susquehanna lateral ramp. Width of area shown in figure is 93 mi. See figure 10 for identification of features.

side of the section (fig. 18), the carbonate rocks of the Trenton Group are repeated. A great deal of transport appears to be required to accomplish this doubling; however, this is a strike line, and the transport direction is into the plane of the figure. At the left center of the figure, the ramp reaches its maximum height, drops in a reverse graben or triangle structure, rises again in a series of northward-directed thrusts, and begins to lose elevation at the south edge of the profile. At the level of the Onondaga Limestone, there are fewer faults, but splays that rise from the arched décollement just above the Onondaga Limestone produce considerable faulting at or near the surface. The splay that reaches the surface at the extreme right side of the record is exposed in a roadcut north of the town of Mathias, W. Va. The type of deformation of this strike-line section more closely resembles a complex dip line and shows many of the same features that are found on dip lines in fold-and-thrust belts. In terms of balancing cross sections, note also that for almost any dip line at right angles

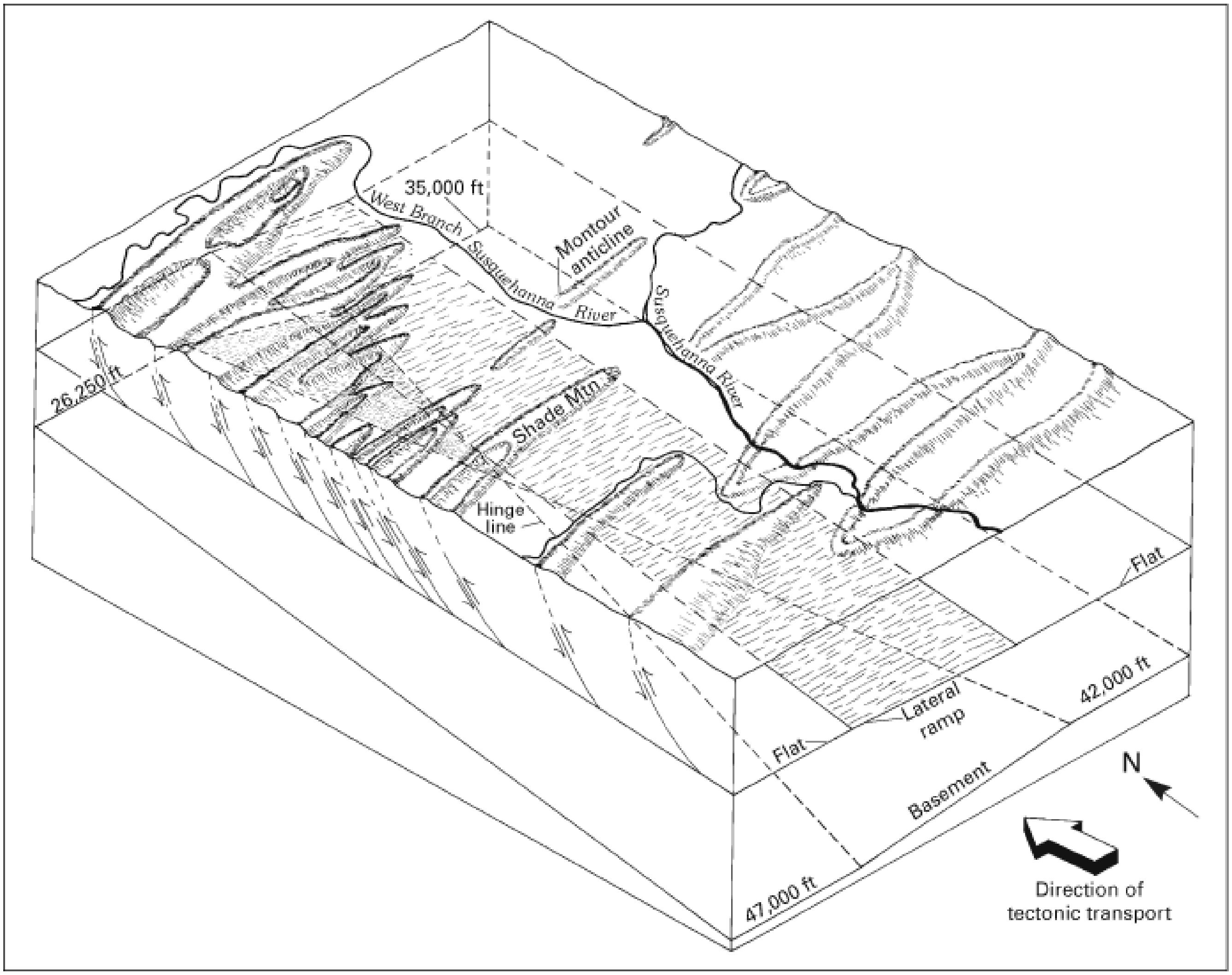



**Figure 10.** Block diagram showing relationship of basement faulting, change in décollement level, and change in fold wavelength to the east and west of the Susquehanna River, central Pennsylvania. Note that the Montour anticline lies directly over the hinge line in the basement.

to this line, beds will have moved both in and out of the dip lines (see Pohn and Coleman, 1991).

In a north-south roadcut, approximately 0.6 mi north of Mathias in Hardy County, W. Va., exposures on both sides of the road reveal an excellent example of an almost completely exposed up-to-the-north lateral ramp (fig. 19). This exposure in the Upper Devonian Brallier Formation appears to be a typical disturbed zone (Pohn and Purdy, 1982, 1988) seen in dip section, with highly folded and faulted beds both overlain and underlain by relatively undisturbed beds. Fold vergence and slickensides show that the transport direction of materials in this outcrop has been in a N. 30° E. direction, nearly perpendicular to the direction of tectonic transport in the Valley and Ridge province (Pohn and others, 1985).

Both northwestward and southeastward continuations of the outcropping lateral ramp at Mathias are suggested on side-looking airborne radar (SLAR) images (fig. 20*A* and *B*). The SLAR data show a number of topographic discontinuities that are parallel to or are along the strike of the exposed lateral ramp at Mathias (M in figure 20*B*).

Southeastward, the ramp area appears to be present as sharp inflections and offsets in the ridges supported by the Devonian Oriskany Sandstone on both sides of the Adams Run anticline, 1.2 and 4.8 mi east of Mathias (A and B in figure 20*B*). These inflections, which narrow the anticline to the southwest, portray an up-to-the-north ramp.

Northwestward, continuations of the across-strike Mathias lateral ramp exposure are manifested by (1) wind

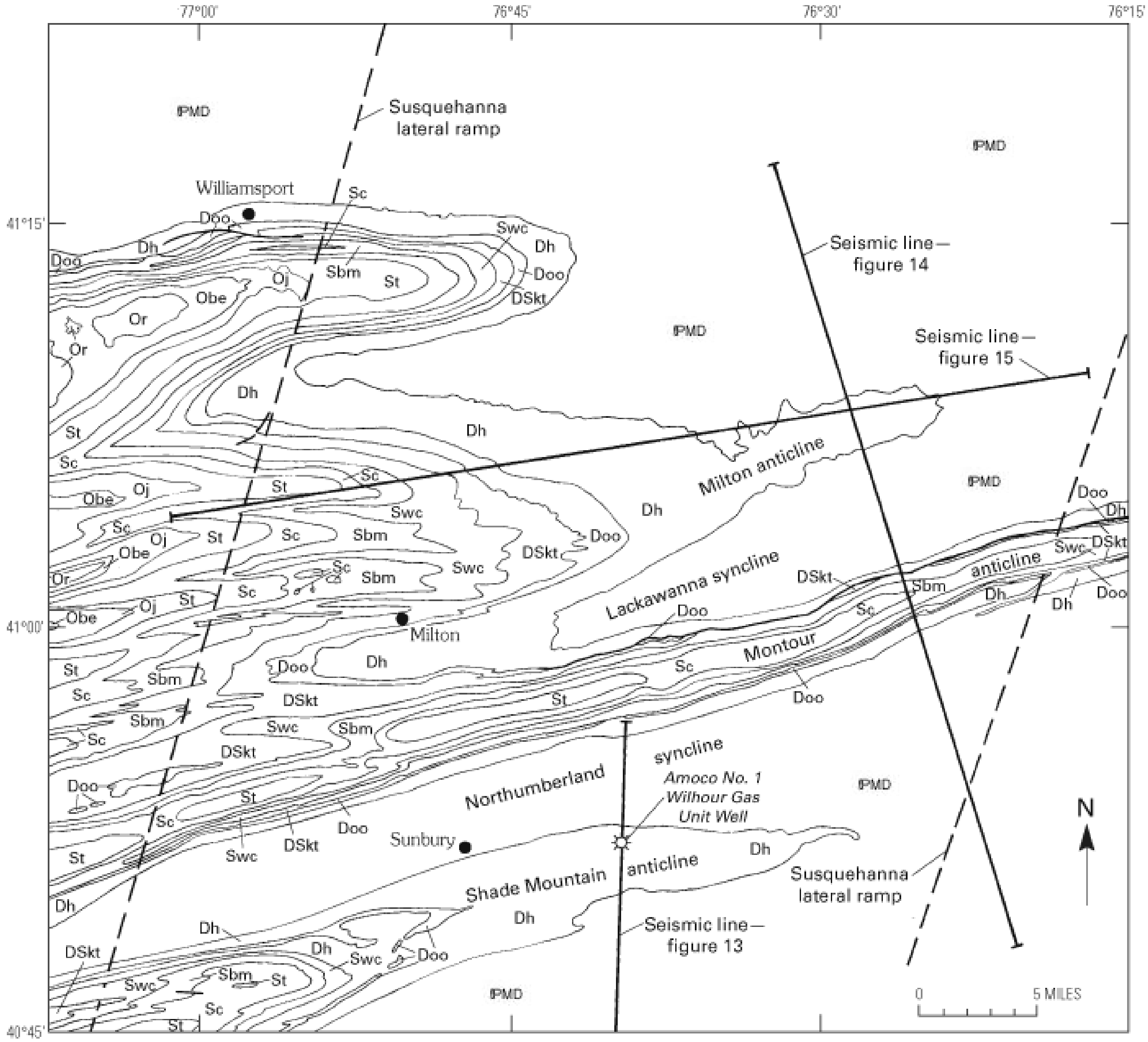



**Figure 11.** Geologic map of central Pennsylvania showing approximate locations of the seismic-reflection profiles (from Berg, 1980). Formation symbols are explained as follows: Or, Reedsville Shale; Obe, Bald Eagle Formation; Oj, Juniata Formation; St, Tuscarora Formation; Sc, Clinton Group (predominantly Rose Hill Formation); Sbm, Bloomsburg Red Beds and Mifflintown Formation, undivided; Swc, Wills Creek Formation; DSkt, Keyser and Tonoloway Formations, undivided; Doo, Old Port Formation and Onondaga Limestone, undivided; Dh, Hamilton Group; PMD, Devonian, Mississippian, and Pennsylvanian formations, undivided. Solid heavy lines indicate faults. Dashed lines show the location of the Susquehanna lateral ramp. From Pohn and Coleman (1991), modified from Berg and Dodge (1981).

and water gaps in the Devonian Brallier, Chemung, and Hampshire Formations from 4.5 to 7.9 mi west of Mathias (C in figure 20*B*); (2) a sharp inflection and landslide in the Elk Horn Mountain anticline 10.9 mi west of Mathias (D in figure 20*B*) (C. Scott Southworth, USGS, oral commun., 1985); and (3) a series of plunging noses (plungeouts) of parasitic anticlines northeast and southwest of the town of Petersburg, W. Va., 15.5 to 19.2 mi west of Mathias (E and F in figure 20*B*). Although the anticlines plunge out in the region of the Petersburg lineament of Wheeler and Sites (1977) and Sites (1978), lines connecting the anticlinal noses both north and south of Petersburg are much closer to the strike of the Mathias lateral ramp (N. 60° W.) than to the Petersburg lineament (N. 70° E.) of Sites (1978),

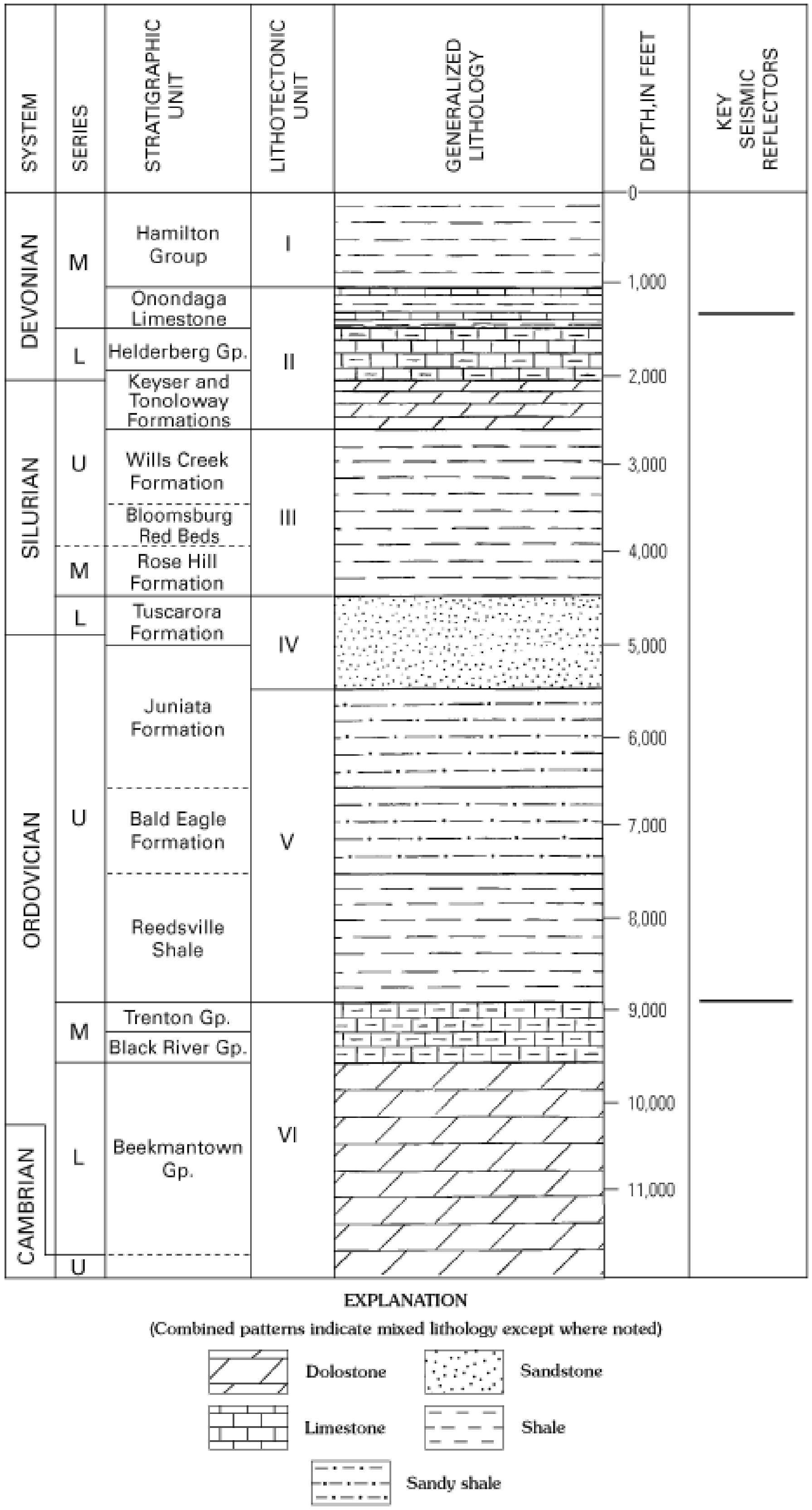



**Figure 12.** Stratigraphic section penetrated by the Amoco No. 1 Wilhour Gas Unit well (shown in figure 13) from the Shade Mountain area of central Pennsylvania. From Pohn and Coleman (1991). Geologic series abbreviated as follows: L, Lower; M, Middle; U, Upper. Stratigraphic thicknesses are estimates. Total depth of the well was 14,737 ft. Gp., Group.

suggesting that the continuation of the structure exposed in the roadcut north of Mathias is the dominant structure in the region. The extensions northwestward from Mathias are subparallel to the Lost River lineament of Sites (1978). In addition, Evans (1989) showed a folded horse block and hypothesized an up-to-the-north oblique ramp in the Great Valley, to the southeast of Mathias.

## HIGHLAND COUNTY LATERAL RAMP

### SURFACE AND GEOPHYSICAL EVIDENCE

Rodgers (1970, p. 17–20) demonstrated that the Elkins Valley and Browns Mountain anticlines terminate along a line that trends N. 72° W. Southeastward along strike, this zone is marked by a series of fold plunges in the Valley and Ridge province east of the Elkins Valley and Browns Mountain anticlines, as well. Progressively southeastward, this zone coincides first with a conspicuous inflection in the Blue Ridge Mountains in Augusta County, Va.; second, with straight trends of the James River; third, with an inflection in the horizontal gradient in the gravity data; and fourth, with a break in pattern in the second vertical derivative of aeromagnetic data off the east coast of Virginia (Krohn and Phillips, 1982).

Field investigations in the area have revealed a thrust fault striking N. 80° E. and dipping 28° to the south, 1.25 mi north of the north end of Snowy Mountain in Pendleton County, W. Va. This fault is the northernmost fault connected with the Highland County lateral ramp. As in the example of the Mathias lateral ramp, this northern border fault appears to be a smaller antithetic fault imbricate to the major ramp whose major movement is up-to-the-south. A strike-line seismic-reflection profile (fig. 21) shows the subsurface nature of the Highland County lateral ramp in Virginia.

### SEISMIC EVIDENCE

Although not nearly as complex a lateral ramp as the more deeply seated Mathias lateral ramp, the Highland County ramp, as seen in the seismic-reflection profile (fig. 21), does show an up-to-the-south configuration. The ramp begins halfway between basement rocks and the carbonate rocks of the Trenton Group, displaces the carbonate rocks slightly, and produces an anticlinal configuration that bows up the Onondaga Limestone several thousand feet. Just below and just above the Onondaga Limestone, faulting increases considerably. Several faults beneath the Onondaga Limestone disappear into a zone several reflectors below the Onondaga Limestone, and some faults rise from a zone several reflectors above the Onondaga Limestone. Only two small faults actually cut the limestone unit itself. This suggests that there are décollements just below and just above the Onondaga Limestone in the area of the Highland County ramp.

## IGNEOUS INTRUSIONS ASSOCIATED WITH LATERAL RAMPS

Of the four lateral ramps mentioned above, three have igneous intrusions mapped at the surface and parallel to the proposed ramps. The Susquehanna, the Pennsylvania-Maryland-West Virginia, and the Highland County ramps all show igneous intrusions directly over and parallel to the lateral ramps. These are the only igneous intrusions present at the surface in the Valley and Ridge province and west of the Little North Mountain fault (which separates the Valley and Ridge province from the Great Valley) in the central Appalachians.

Although the presence of these igneous intrusions indicates a connection to basement, no obvious basement faulting can be seen in the seismic-reflection profile of the Highland County ramp (fig. 21). However, an additional seismic-reflection profile (fig. 22) does show a peculiar signature in an otherwise featureless basement. This anomaly lies directly below an igneous dike exposed at the surface. The seismic-reflection profile of the Mathias lateral ramp (fig. 18) shows a similar signature in an almost featureless basement. If this signature is characteristic of an igneous body at depth, then the Mathias ramp may also have been affected by igneous activity.

# ADDITIONAL LATERAL RAMPS IN THE CENTRAL APPALACHIANS

At least five additional hypothesized lateral ramps are present in the central Appalachians of Pennsylvania to Virginia (fig. 23*A* and *B*). They are the Wilkes-Barre ramp, the Seven Mountains ramp, the Tyrone-Mount Union ramp, the Bedford ramp, and the Lexington ramp. The evidence for these ramps varies from multiple fold plunges at Seven Mountains to fold plunges, faulting at the surface, and reported flower structures (Biddle and Christie-Blick, 1985) in the subsurface of the Bedford ramp. Another lateral ramp may exist at Roanoke, Va.

## WILKES-BARRE LATERAL RAMP

The Wilkes-Barre lateral ramp (fig. 23*B*) is defined by a series of fold plunges across strike, which can be seen on the SLAR images and more obviously on the geologic map of Pennsylvania (Berg and Dodge, 1981). In addition, the overall straight trend of the Susquehanna River from

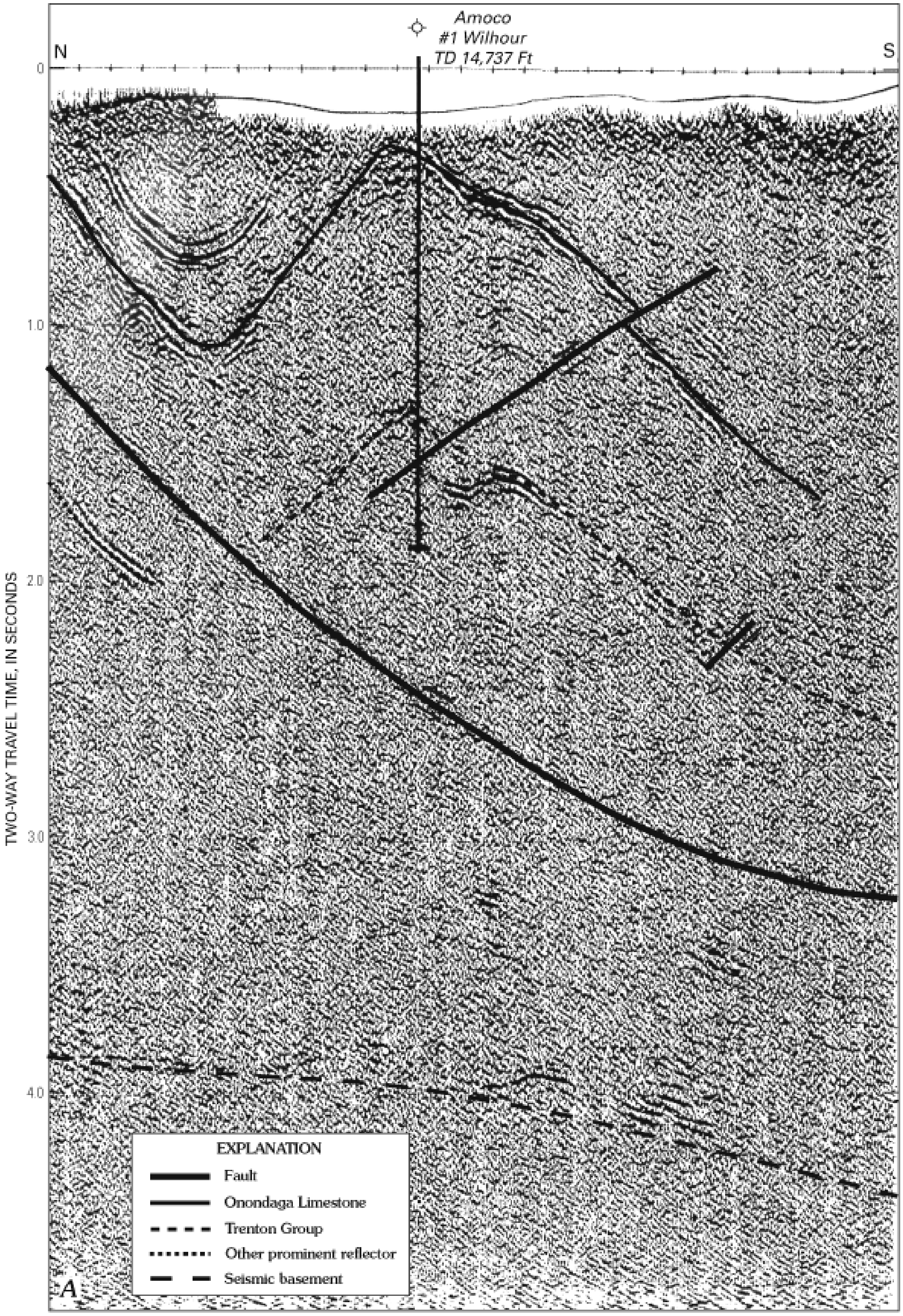



**Figure 13 (above and facing page).** *A*, Dip-line seismic-reflection profile across the Shade Mountain anticline shown in figure 11. Faults are shown by solid lines; relative direction of movement is shown by arrows. Dashed lines are key reflectors. Profile shows seismic data collected along a line approximately 13 mi long. From Pohn and Coleman (1991). *B*, Same profile as *A* but uninterpreted.

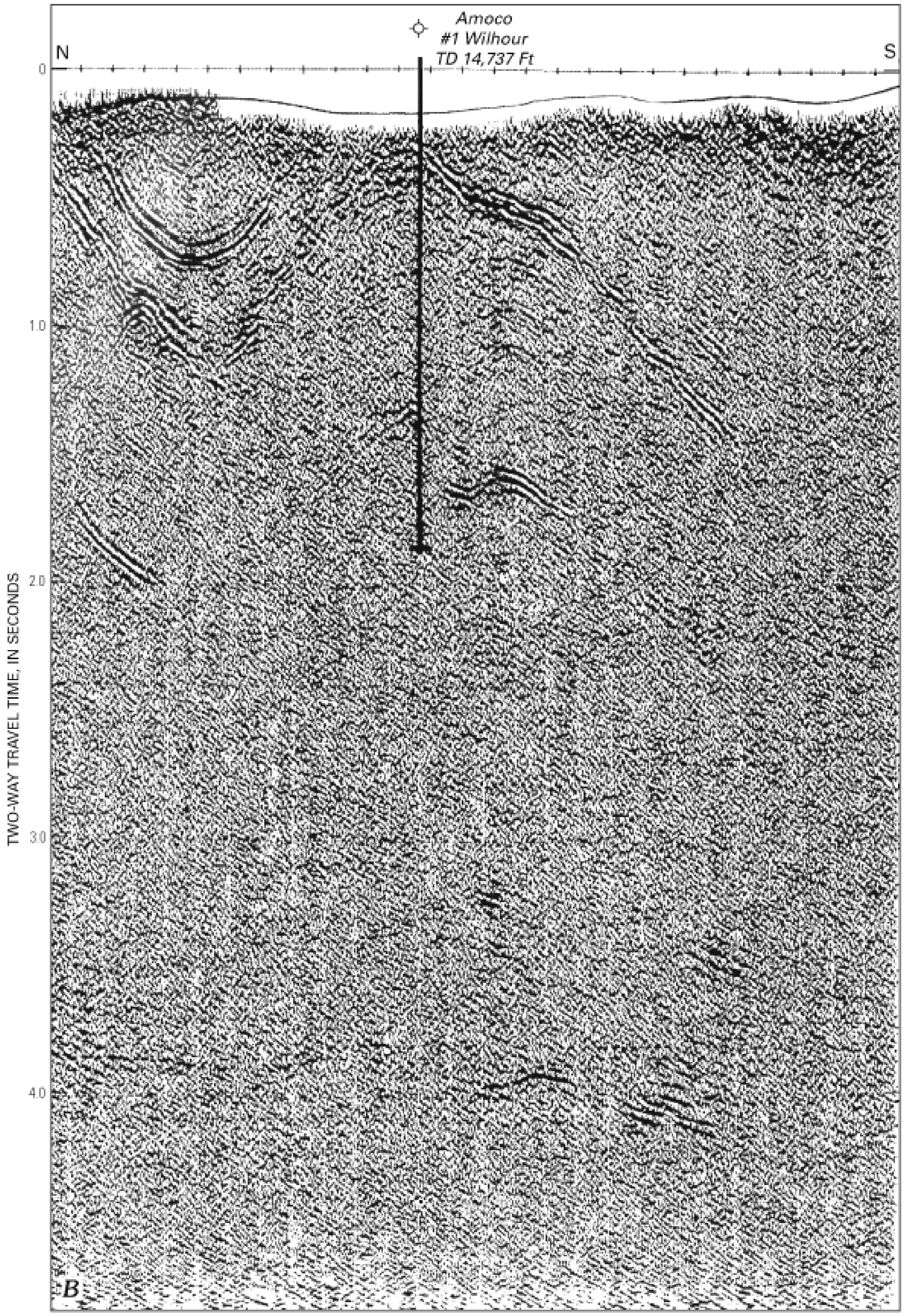



**Figure 13.** Continued.

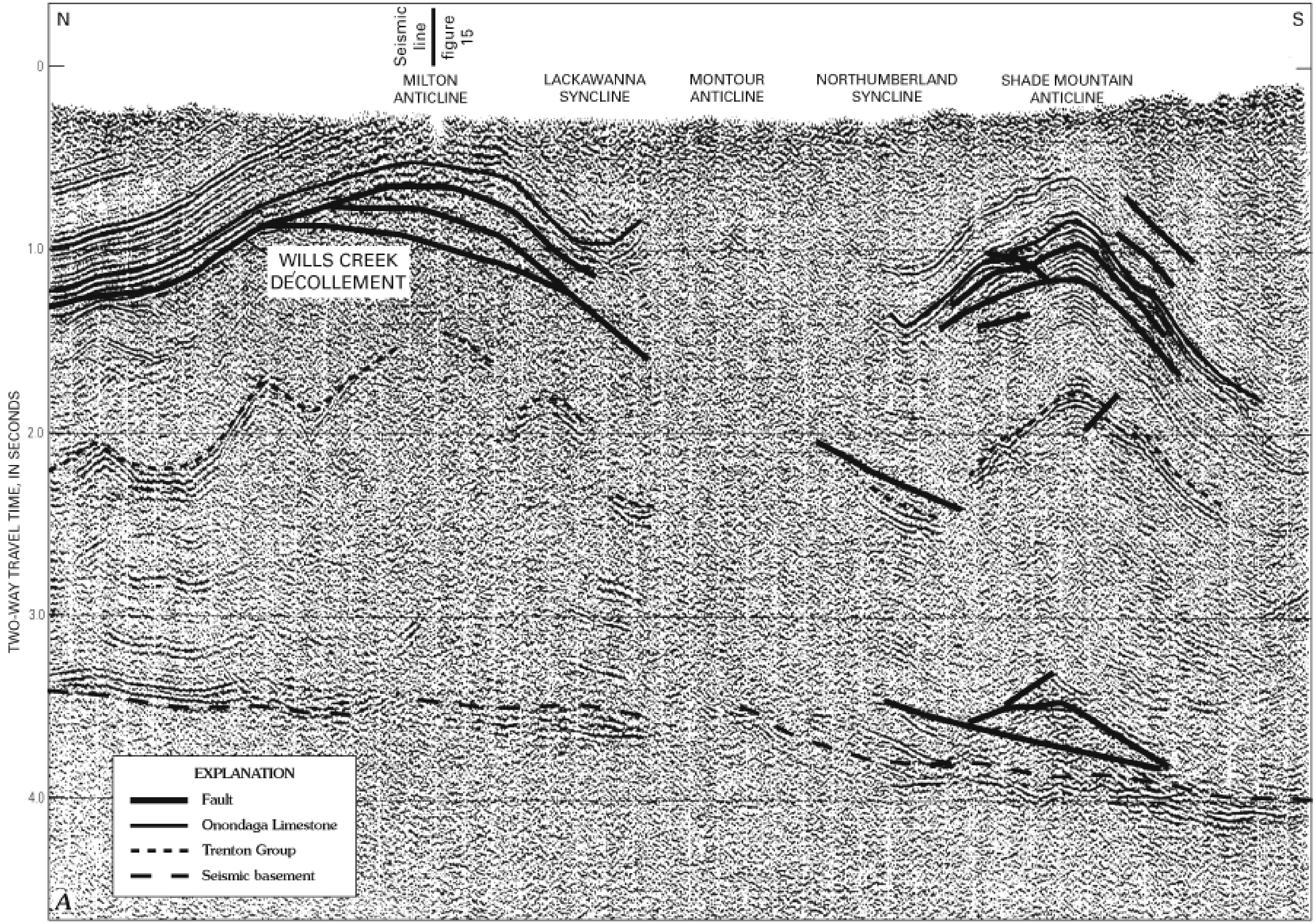



**Figure 14 (above and facing page).** *A*, Dip-line seismic-reflection profile across the Milton and Montour anticlines shown in figure 11. Solid lines are interpreted faults; dashed lines are key reflectors. From Pohn and Coleman (1991). Profile shows seismic data collected along a line approximately 36 mi long. *B*, Same profile as *A* but uninterpreted.

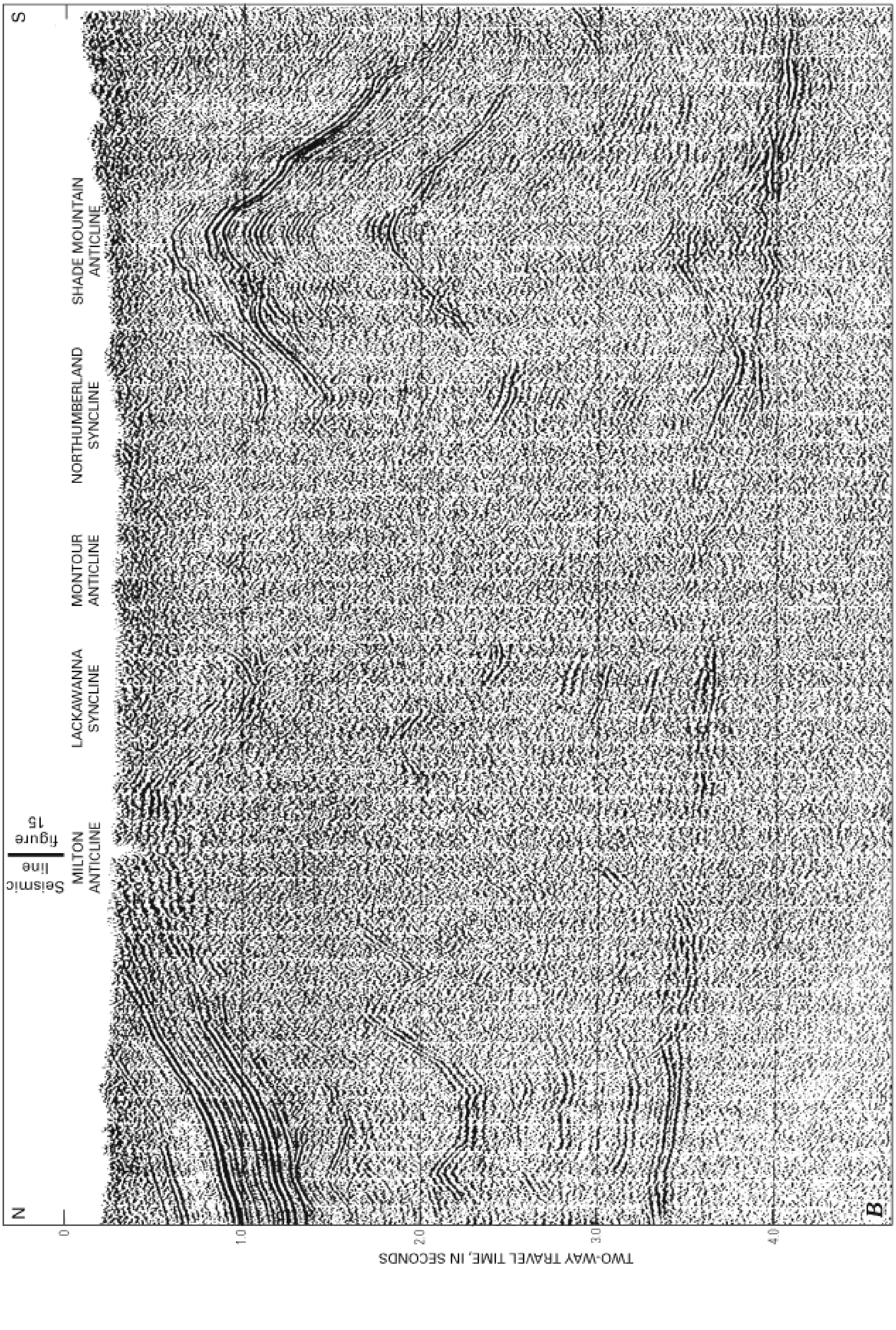



**Figure 14.** Continued.

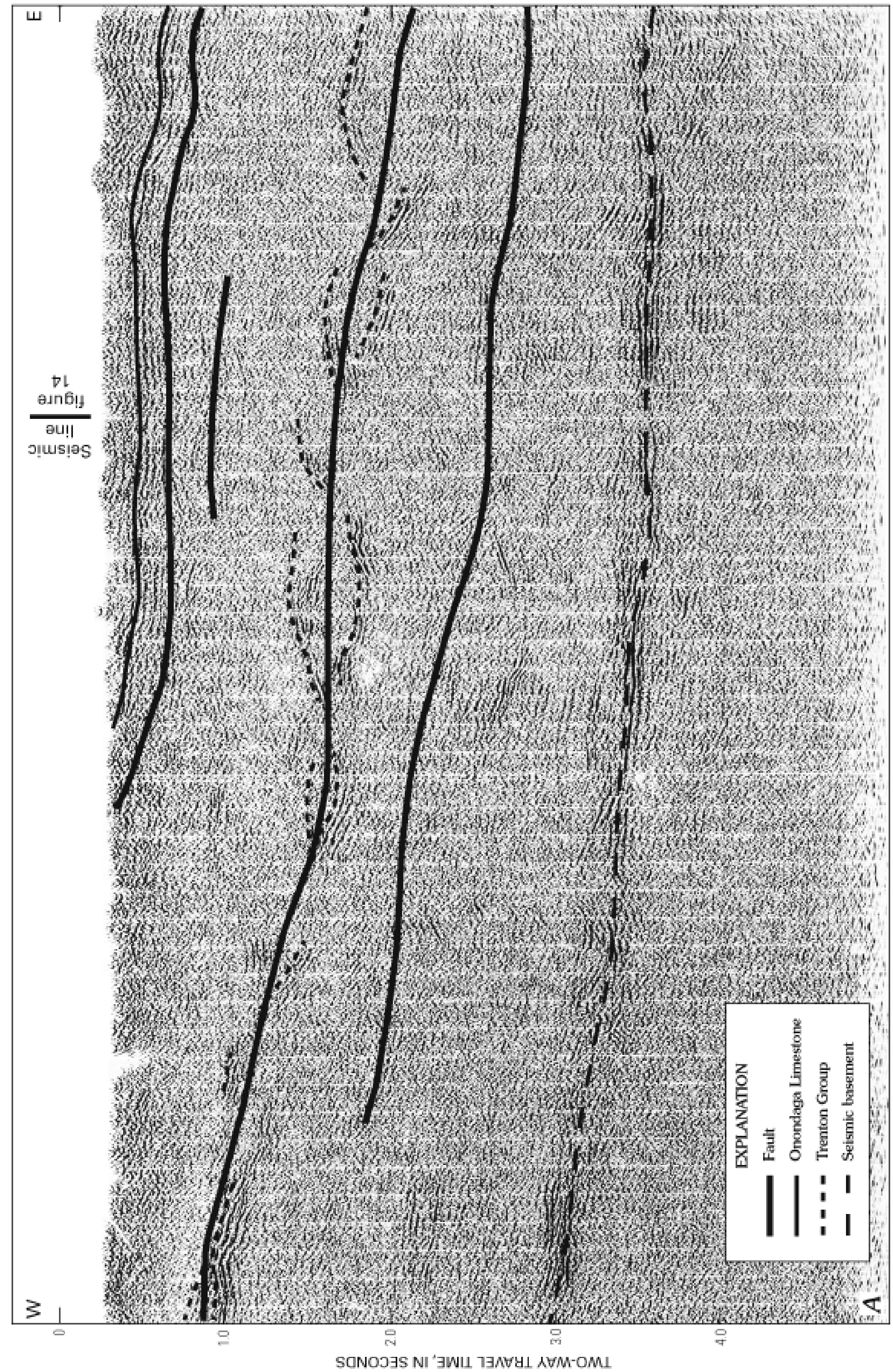



**Figure 15 (above and facing page).** *A*, Strike-line seismic-reflection profile parallel to the regional structure (fig. 11) but perpendicular to the Susquehanna lateral ramp (figs. 10, 11). Solid lines are interpreted faults; dashed lines are key reflectors. From Pohn and Coleman (1991). Profile shows seismic data collected along a line approximately 39 mi long. *B*, Same profile as *A* but uninterpreted.

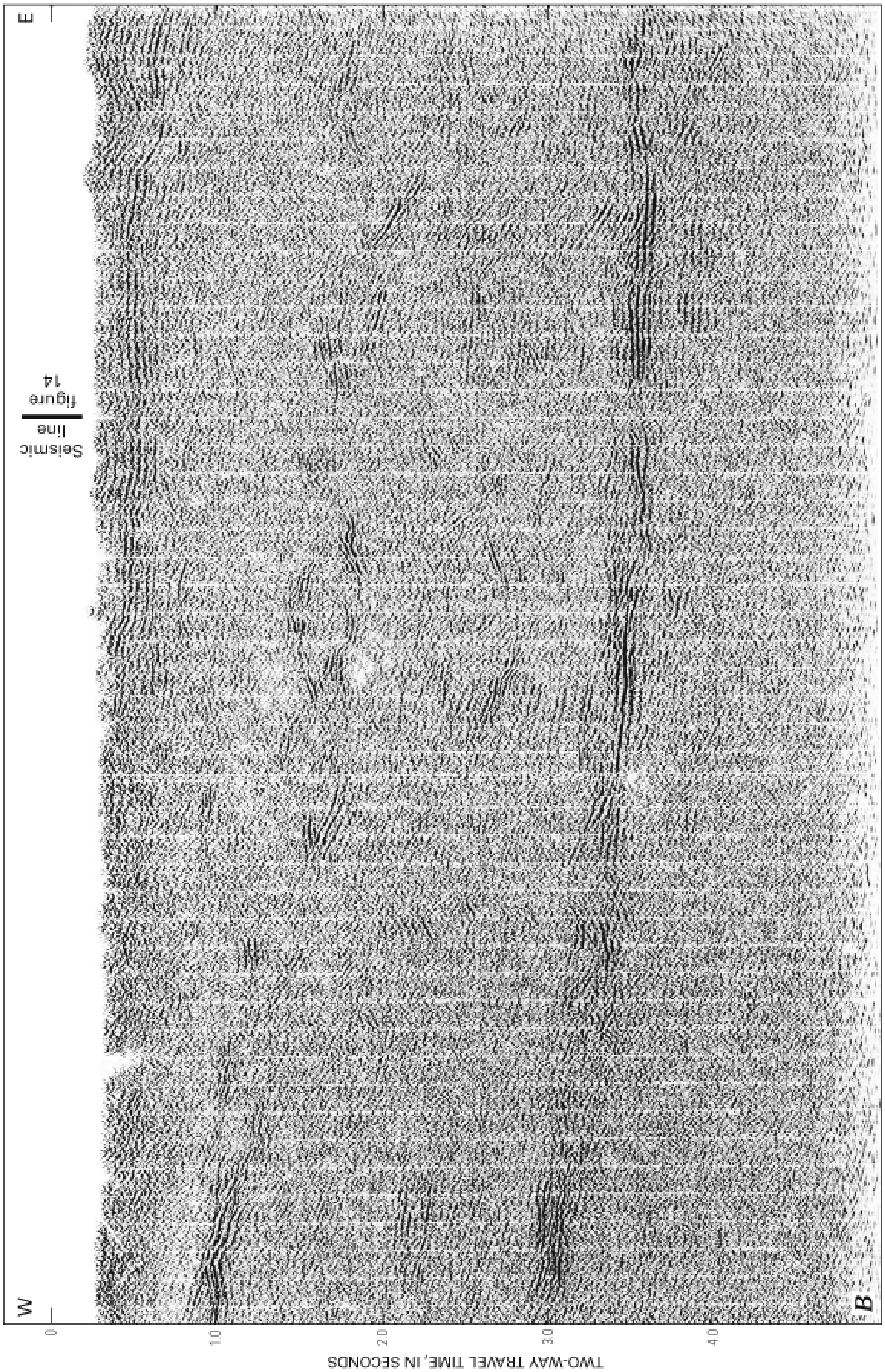



**Figure 15.** Continued.

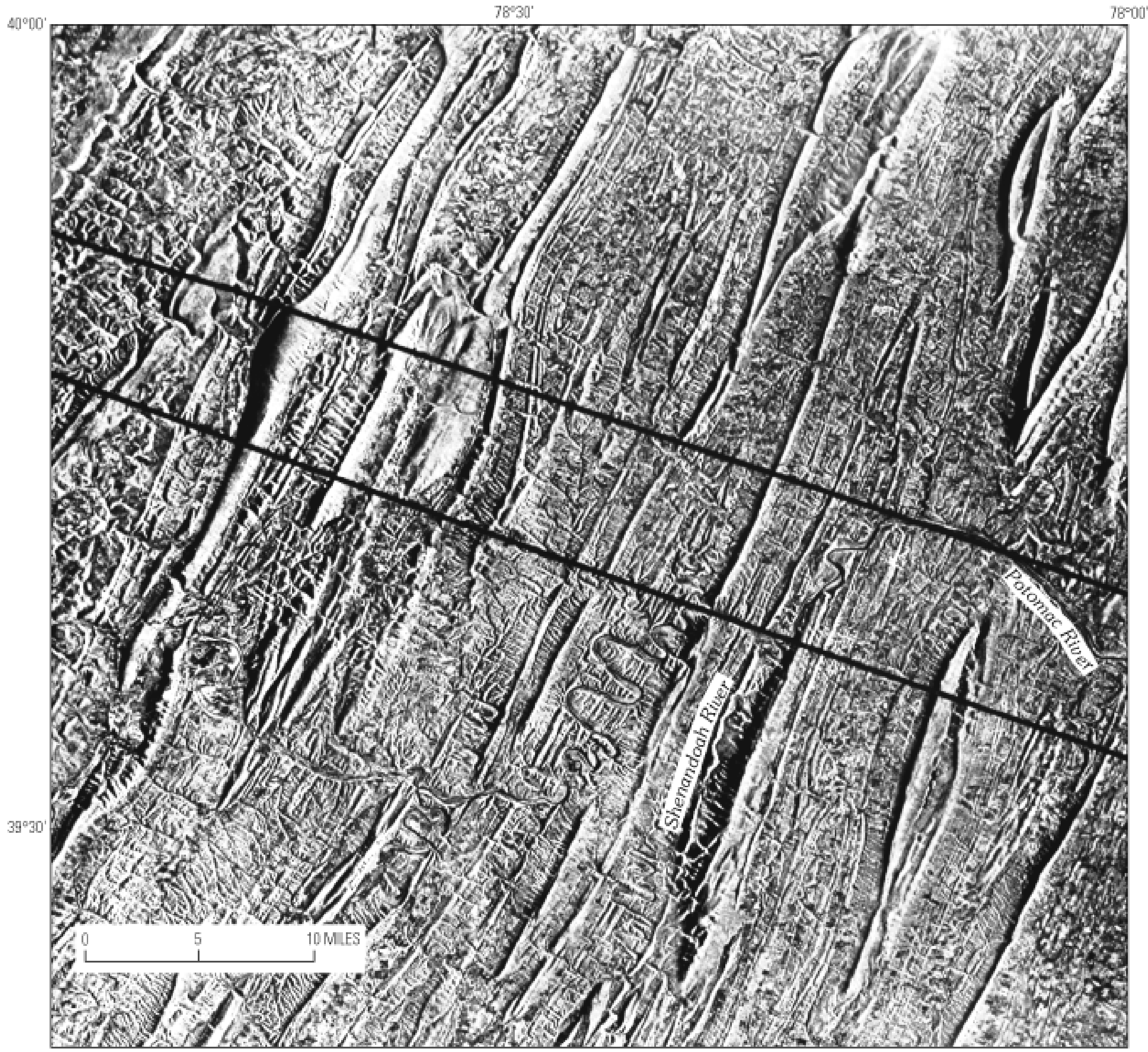



**Figure 16.** Side-looking airborne radar (SLAR) image of part of the Cumberland 1°×2° quadrangle showing the narrowing of folds to the south across the Pennsylvania-Maryland-West Virginia lateral ramp (area within the crosscutting parallel lines).

Towanda, Pa., to the Lackawanna syncline and the generally straight course of the Delaware River from Easton, Pa., to Trenton, N.J., are directly over the proposed ramp. Eleven occurrences of anomalous coarse pebble conglomerates have been described by Sevon (1979) along this ramp (for more discussion on the importance of conglomerates, see the section below on the Fincastle Conglomerate).

## SEVEN MOUNTAINS LATERAL RAMP

The Seven Mountains lateral ramp in Pennsylvania underlies folds plunging to the west at Seven Mountains and has folds plunging to the east at Doubling Gap, Pa. (fig. 23*A*). The most probable reason for the opposite plunges at opposite ends of the ramp is a décollement that

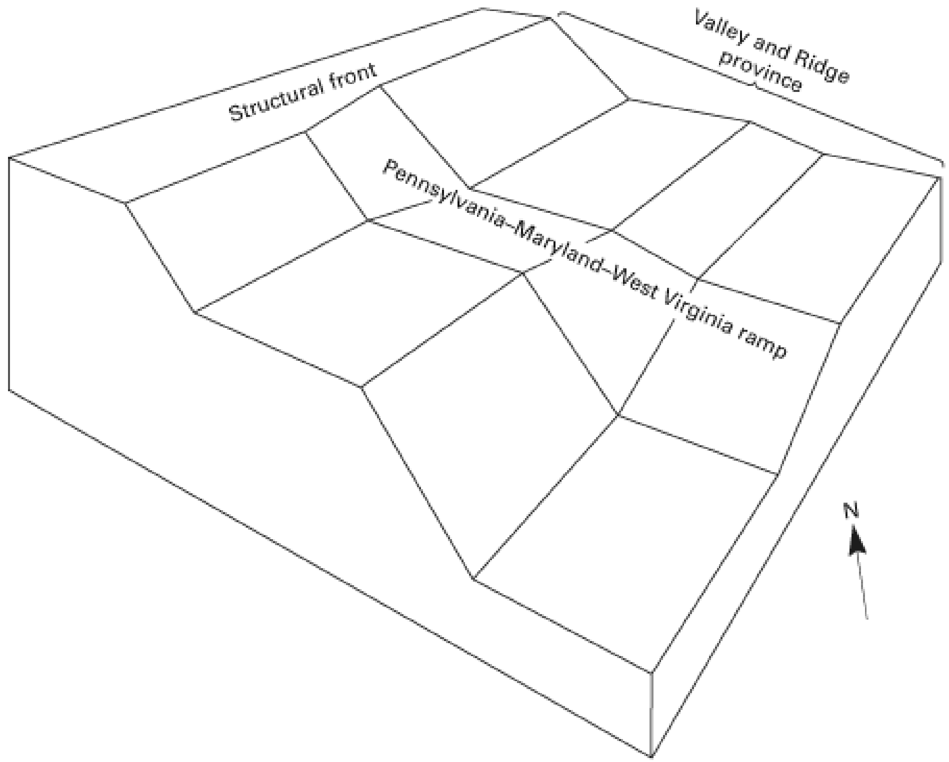



**Figure 17.** Block diagram showing the eastward shift of the Appalachian structural front south of the Pennsylvania-Maryland-West Virginia lateral ramp.

is up-to-the-west at its northern extremity and up-to-the-east at its southern extremity (fig. 24). Between these two extremities, there is an area below Jacks Mountain where the ramp has no displacement, which represents a null zone. The null zone is similar to the Montour anticline across the Susquehanna ramp, which does not exhibit any plunge (fig. 10).

## TYRONE-MOUNT UNION LATERAL RAMP

The Tyrone-Mount Union lateral ramp (fig. 23*A*) in Pennsylvania is represented by abrupt changes in fold wavelength, plungeouts of folds, and straight trends of the Juniata River crossing the Valley and Ridge province. Parrish and Lavin (1982), Lavin and others (1982), and Gold and Pohn (1985) discussed the presence of geophysical discontinuities in both gravity and magnetic data along the hypothesized ramp. As in the example of the Seven Mountains ramp, the Tyrone-Mount Union ramp is likely to be up-to-the-west on the northern end and up-to-the-east on its southern end (north of Shippensburg, Pa.).

## BEDFORD LATERAL RAMP

The Bedford lateral ramp in Pennsylvania is represented by a discontinuous line of faults (Berg and Dodge, 1981), fold plunges, changes in fold wavelength, and discontinuities in the South Mountain area of the Blue Ridge province. Proprietary seismic data show the presence of a flower structure in the subsurface (James Farley, petroleum consultant, oral commun., 1981). In addition, a small portion of a lateral ramp can be seen on Pennsylvania State Route 30, 328 ft to the west of its intersection with Interstate Route 76 (Pennsylvania Turnpike).

## LEXINGTON LATERAL RAMP

The Lexington lateral ramp in Virginia is manifested by a series of fold plunges; changes in fold wavelengths; changes in the frequency of faults mapped at the surface; long, straight trends in the upper reaches of the James River; discontinuities in the Blue Ridge province; and interruption of Mesozoic basins.

## ROANOKE LATERAL RAMP

There may be more surface stratigraphic and structural information available for the area above the hypothesized Roanoke lateral ramp than for any other lateral ramp in the Appalachians. Unfortunately, no seismic-reflection profiles are available and thus the subsurface aspect of the ramp is unknown. However, the abundant stratigraphic and structural evidence strongly suggests that there is a

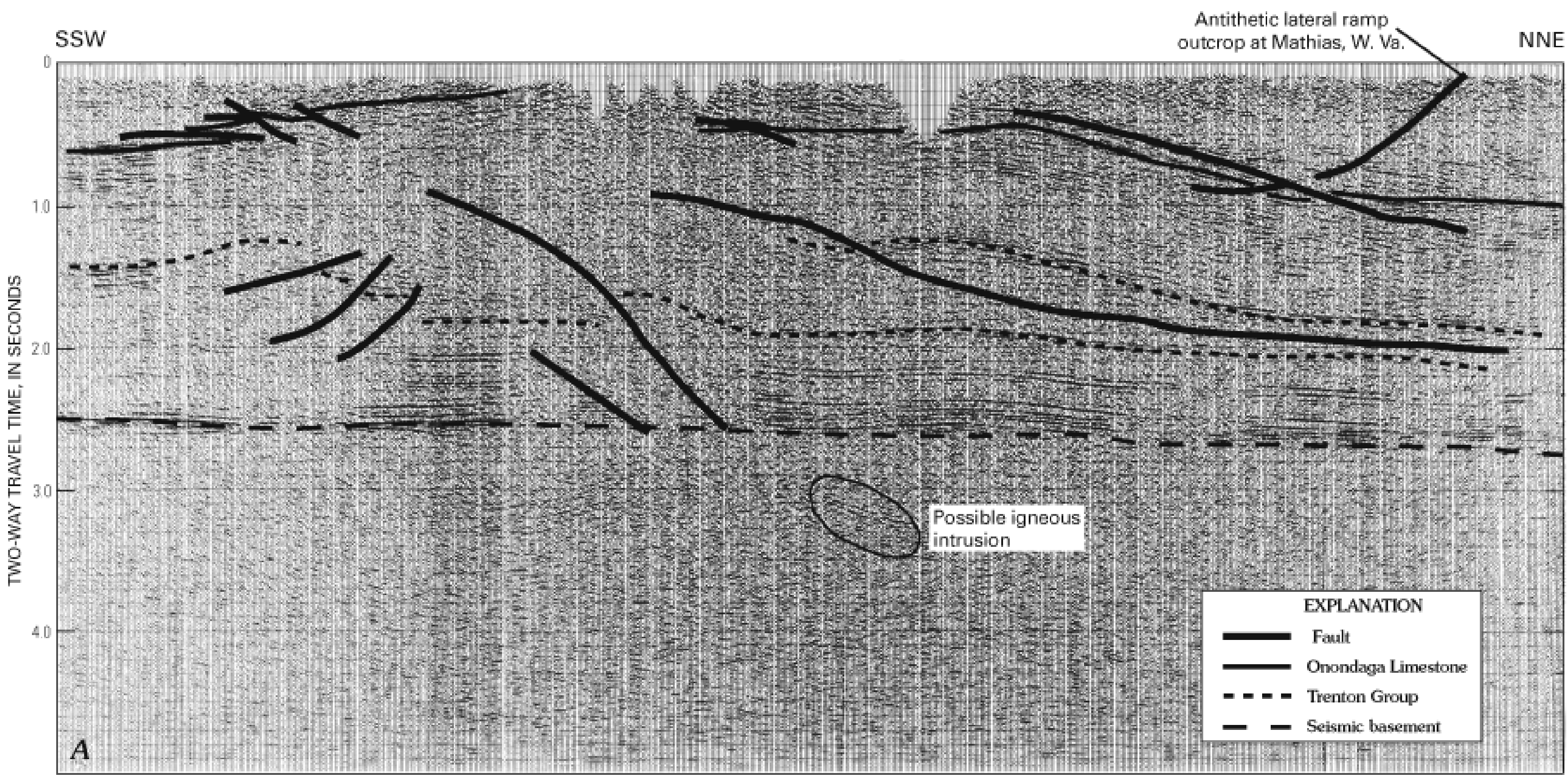



**Figure 18 (above and facing page).** *A*, Strike-line seismic-reflection profile of the Mathias lateral ramp in West Virginia. Profile shows seismic data collected along a line (fig. 20*A*) approximately 16 mi long. *B*, Same profile as *A* but uninterpreted.

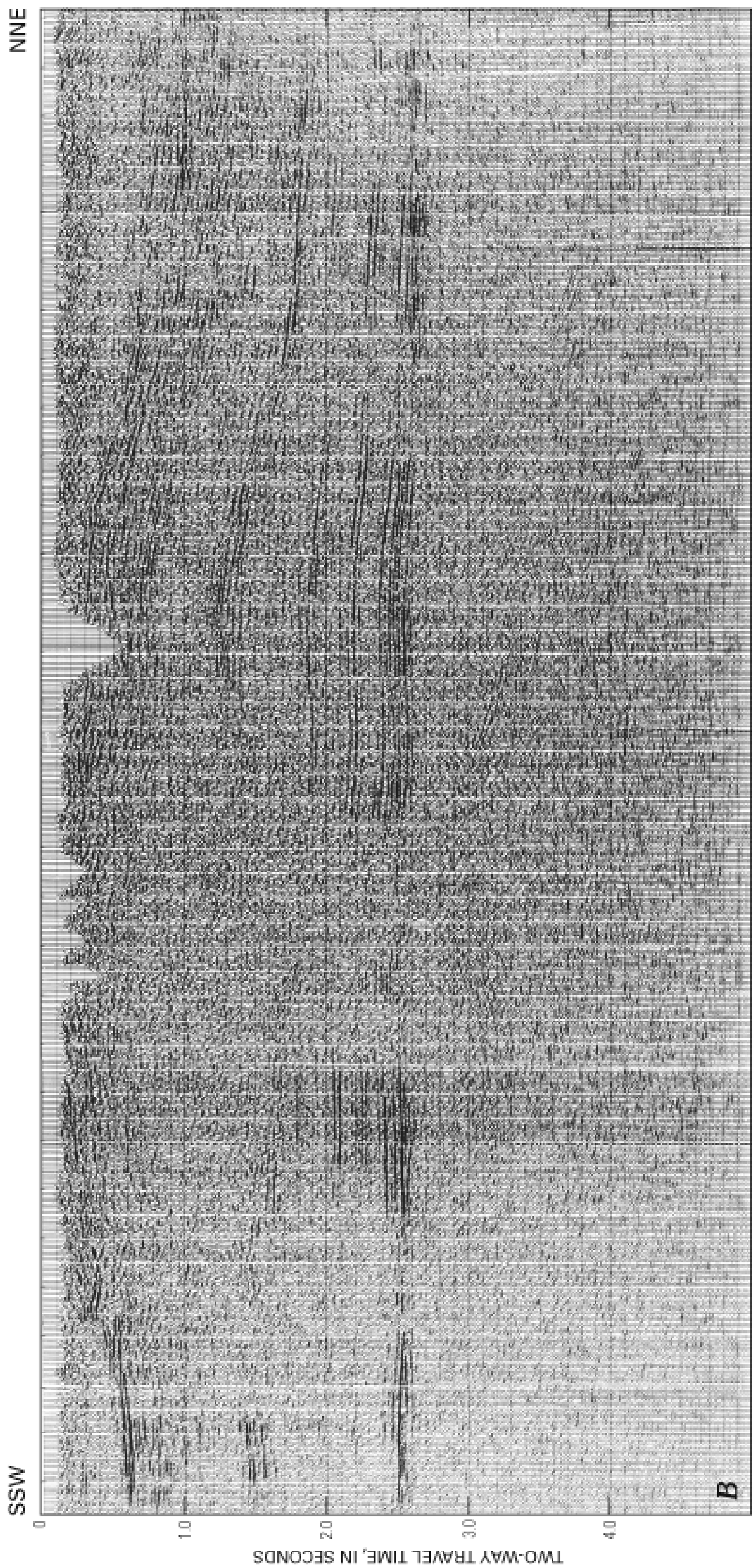



**Figure 18.** Continued.

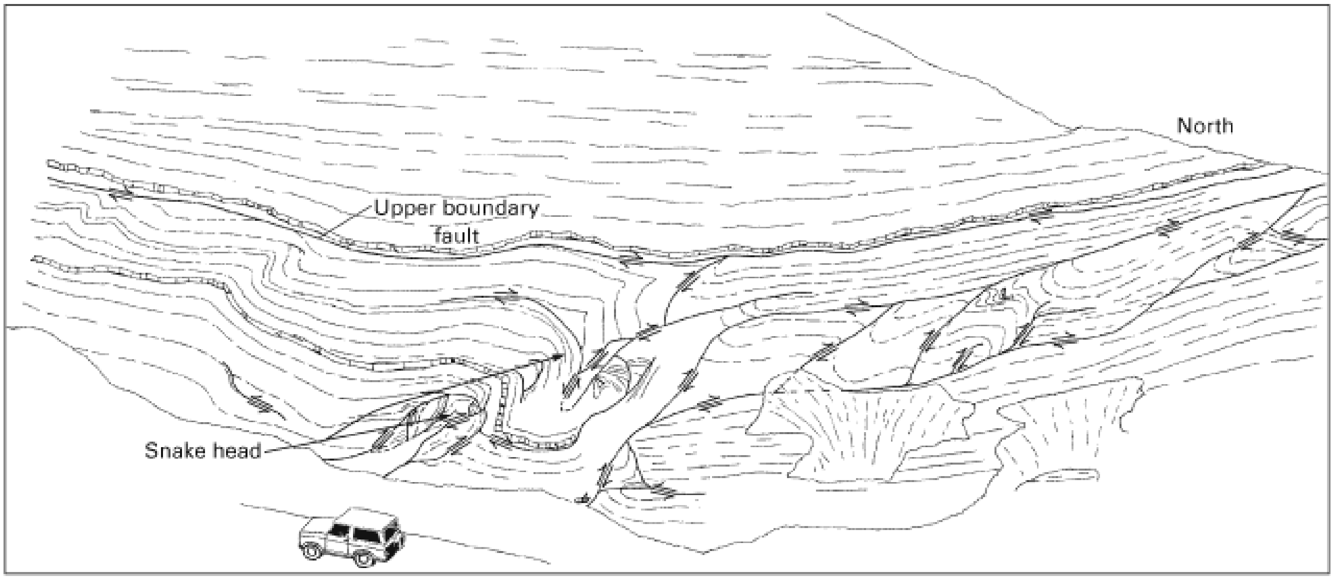



**Figure 19.** Sketch of a roadcut 0.6 mi north of Mathias, W. Va., along West Virginia Route 259, showing cross section of an up-to-the-north lateral ramp. Arrows indicate relative movement along faults. Note the "snake head" and upper boundary fault. All these features are perpendicular to the direction of tectonic transport. This exposure is probably the northernmost thrust fault in the Mathias lateral ramp system and is antithetic to the main system, which is up-to-the-south.

significant lateral ramp at Roanoke, Va., that coincides with the junction of the central and southern Appalachians.

A major difference between the central and southern Appalachians is that, in the central Appalachians, the décollements are mostly at considerable depth, whereas in the southern Appalachians, the décollements are seen at the surface (Rodgers, 1970, p. 39–43; Lowry and others, 1971, p. 2–6). This change in décollement level coincides with a decrease in depth to basement from the central to the southern Appalachians. The major exception to this concept is the Pulaski décollement, which is seen at the surface in both the central and southern Appalachians. The décollements do not suddenly come into being at the juncture but, instead, rise steeply to the surface along a lateral ramp, which is up-to-the-south. Figure 25 shows the major imbricate faults as being tangential to the décollement, as has been documented from seismic data. Because the décollements are tangential to the imbricate faults, the spacing of these imbricate faults just above the décollements is wider than the spacing at a slightly higher level above the décollements. Concomitantly, the fold wavelength is also wider just above the décollements than it is at a higher level. Wavelengths of folds that have become longer the higher they are above the décollement also are longer immediately above the décollement. This is precisely what is seen as the juncture zone is crossed (fig. 25).

## FINCASTLE CONGLOMERATE: AN INDICATOR OF THE ROANOKE LATERAL RAMP

The Fincastle Conglomerate of Middle Ordovician age lies 0.6 to 1.25 mi north of the town of Fincastle, Va. (fig. 26). This deposit, described by Stow and Bierer (1937), Butts (1940), Decker (1952), and Kellberg and Grant (1956), is composed of coarse pebbles derived from most of the Cambrian and Ordovician formations lower in the nearby stratigraphic section and possibly even from the basement complex to the southeast of the Blue Ridge. The pebbles in the Fincastle Conglomerate are subangular to subrounded and are composed mostly of limestone with some quartz, vein quartz, sandstone, chert, and siltstone. Most of these rock types would not retain the observed shapes if they were transported very far from their origin. In addition, the deposits are geographically restricted to the middle of the proposed ramp and do not occur outside the confines of the ramp area. Kellberg and Grant (1956) proposed that the Fincastle Conglomerate is a submarine channel deposit whose materials were shed from nearby highlands located to the southeast. This idea could tie to the tectonic picture of lateral ramps proposed here if those highlands were related to the arriving Taconian thrust sheets, which contained most of the stratigraphic units whose sediments are found in the Fincastle Conglomerate clasts. In fact, Kellberg and Grant (1956) also described five additional anomalous Middle Ordovician coarse-pebble conglomerates in the southern Appalachians. Of the six deposits described by them, four are located directly on the lateral ramps proposed here.

#### CHANGES IN UNIT THICKNESS AND LITHOLOGIES

Oliver and others (1971), Dorobek and Read (1986), and B.A. Ferrill and W.A. Thomas (City of Huntsville, Ala., and University of Kentucky, respectively, written commun., 1990) discussed or illustrated a dramatic thinning of Upper Silurian and Lower Devonian formations at the proposed location of the Roanoke lateral ramp and across the strike of the fold belt. Oliver and others (1971) showed a decrease in thickness of the total Silurian and Devonian section from 6,000 ft to 4,000 ft (northeast to southwest) and a further decrease in thickness to 2,000 ft at the proposed New River lateral ramp (discussed in the following section). Dorobek and Read (1986) showed thinning of Helderberg Group rocks from 262 ft to 131 ft at the Roanoke ramp. Oliver and others (1971) also showed this thinning of Helderberg Group rocks and showed a change from limestone to sandstone (northeast to southwest) at the Roanoke ramp. B.A. Ferrill and W.A. Thomas (see above, written commun., 1990) showed a thinning of Devonian rocks above the Onondaga Limestone equivalent from 6,562 ft to 1,641 ft (northeast to southwest) at the Roanoke ramp and a thinning of Devonian rocks below the top of the Onondaga Limestone equivalent from 492 ft to less than 328 ft at the ramp. All these authors presented evidence of deep water to the northeast and shallower water to the southwest starting at least in Late Silurian time. Thus, the roots below the Roanoke lateral ramp, and perhaps the lateral ramp itself, may have formed during the Taconian orogeny or earlier.

### COARSE-PEBBLE CONGLOMERATES RELATED TO OTHER LATERAL RAMPS

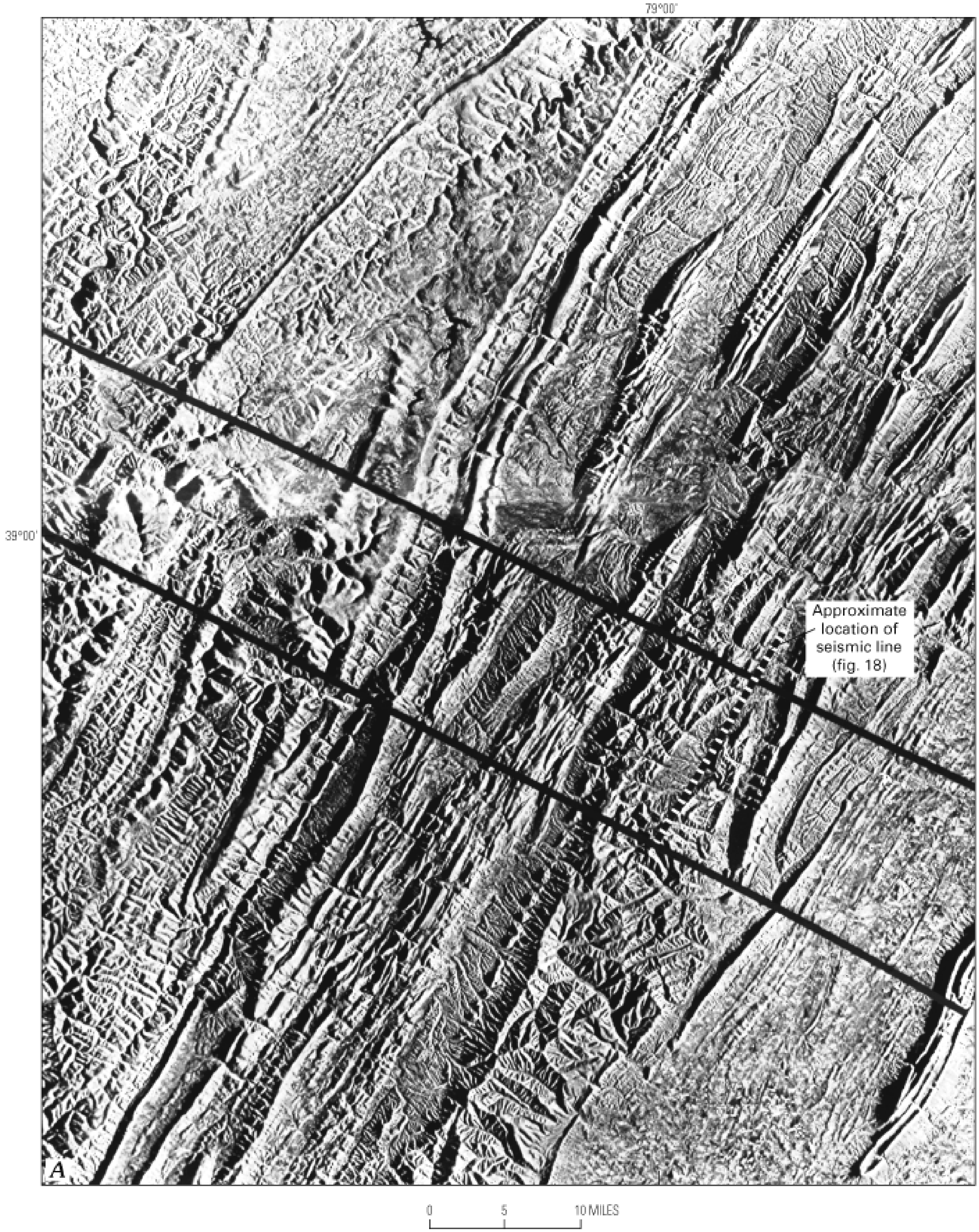
Sevon (1979) reported on 19 anomalous coarse-pebble conglomerates (his polymictic diamictite) in the Spechty Kopf and Rockwell Formations of Late Devonian and Early Mississippian age in Pennsylvania. Of those occurrences, 16 are directly on lateral ramps as follows: 11 are located on the Wilkes-Barre ramp, 4 are on the Susquehanna ramp, and 1 is on the Pennsylvania-Maryland-West Virginia ramp. Sevon (1979) stated that "the diamictites have narrow distribution parallel to depositional strike but have considerable distribution normal to the depositional strike. Deposits in Carbon County in northeastern Pennsylvania have a width of occurrence of about 3 km parallel to depositional strike [northeast-southwest], but occur over a distance of about 64 km normal to depositional strike [north-south]." This pattern of deposition is similar to that of the Fincastle Conglomerate.

Only the largest and most conspicuous lateral ramps that cross the entire fold belt in the Appalachians are discussed in this report, but it is clear from the section on scale independence that lateral ramps should also exist at many scales, from inches to miles. The existence of lateral ramps at the various scales can be documented in the field (the relatively small lateral ramp 0.6 mi north of Mathias is just one example). The conglomerates that are not associated with the large lateral ramps discussed in previous sections may have been shed off of smaller lateral ramps.

## LATERAL RAMPS IN THE SOUTHERN APPALACHIANS

If we assume that lateral ramps in the southern Appalachians manifest themselves in the same manner as those in the central Appalachians, then a close examination of SLAR data should enable detection of these ramps by using the same criteria. Features such as zones of fold plunges, changes in fold wavelength, discontinuities in the Blue Ridge province, straight river trends, and changes in frequency of faults mapped in the field may indicate the presence of lateral ramps at depth. Radar and field data have provided a number of candidate sites for such lateral ramps (fig. 27*A* and *B*). The radar data also provided unanticipated information relating to the positions of lateral ramps. Although many of the proposed ramps in the southern Appalachians are essentially perpendicular to the local strike of the Valley and Ridge province, several other ramps are apparent whose strikes are close to N. 70° W., a direction very nearly parallel to the trend of lateral ramps in the central Appalachians. These N. 70° W.-trending ramps are manifested not only by zones of fold plunges and changes in fold wavelength in the Valley and Ridge province, but by swarms of lineaments or long, relatively uninterrupted lineaments in the Blue Ridge and in a few places in the Piedmont provinces.

Perhaps the best example of such a lineament zone is seen on the radar image of the Winston-Salem and Johnson City 1°×2° quadrangles (fig. 28). On this image, the lineament zone is seen not only within the main body of the Blue Ridge province, but it appears to cross the northward extension of the Brevard fault zone as well. This lineament zone (herein named the Kingsport lateral ramp) strikes N. 73° W. and crosses the Precambrian rocks of the Blue Ridge province but is apparently only weakly expressed in the Paleozoic rocks of the Valley and Ridge province. The local cross-strike lateral ramp (herein named the Johnson City lateral ramp), which strikes N. 17° W., crosses both the Valley and Ridge and Blue Ridge provinces. These two ramps intersect at Johnson City, Tenn. One ramp is parallel to ramps in the central Appalachians and one is perpendicular to the local strike of the southern Appalachians. The


79°00'
39°00'
Approximate location of seismic line (fig. 18)
A
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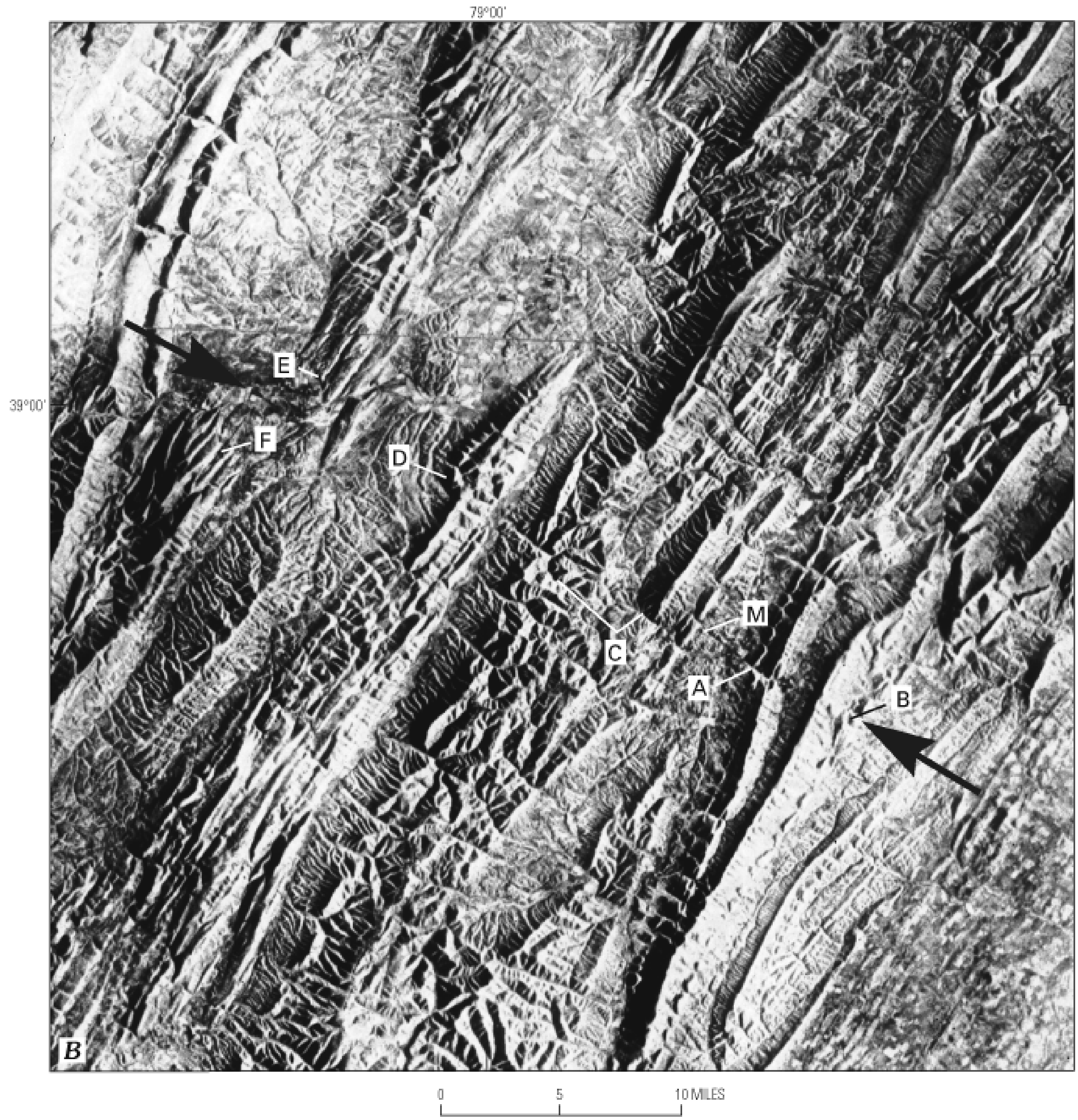



**Figure 20 (previous page and above).** Side-looking airborne radar (SLAR) images of parts of the Cumberland and Charlottesville 1°×2° quadrangles showing the boundary lines enclosing the Mathias lateral ramp. East-west line across image is a mosaic line. *A*, Image showing approximate location of the strike-line seismic-reflection profile in figure 18 (shown by ticked line). *B*, Inset from right-center of *A*. Heavy arrows mark the Mathias lateral ramp. Key features are as follows: A and B, offsets of ridges underlain by Oriskany Sandstone, illustrating the topographic discontinuities along the northern hinge of the ramp; C, wind and water gaps; D, inflection and landslide in Elk Mountain anticline; E and F, termination of subsidiary anticlines. M, Mathias, W. Va. Scene is approximately 34 mi wide. From Pohn and others (1985).

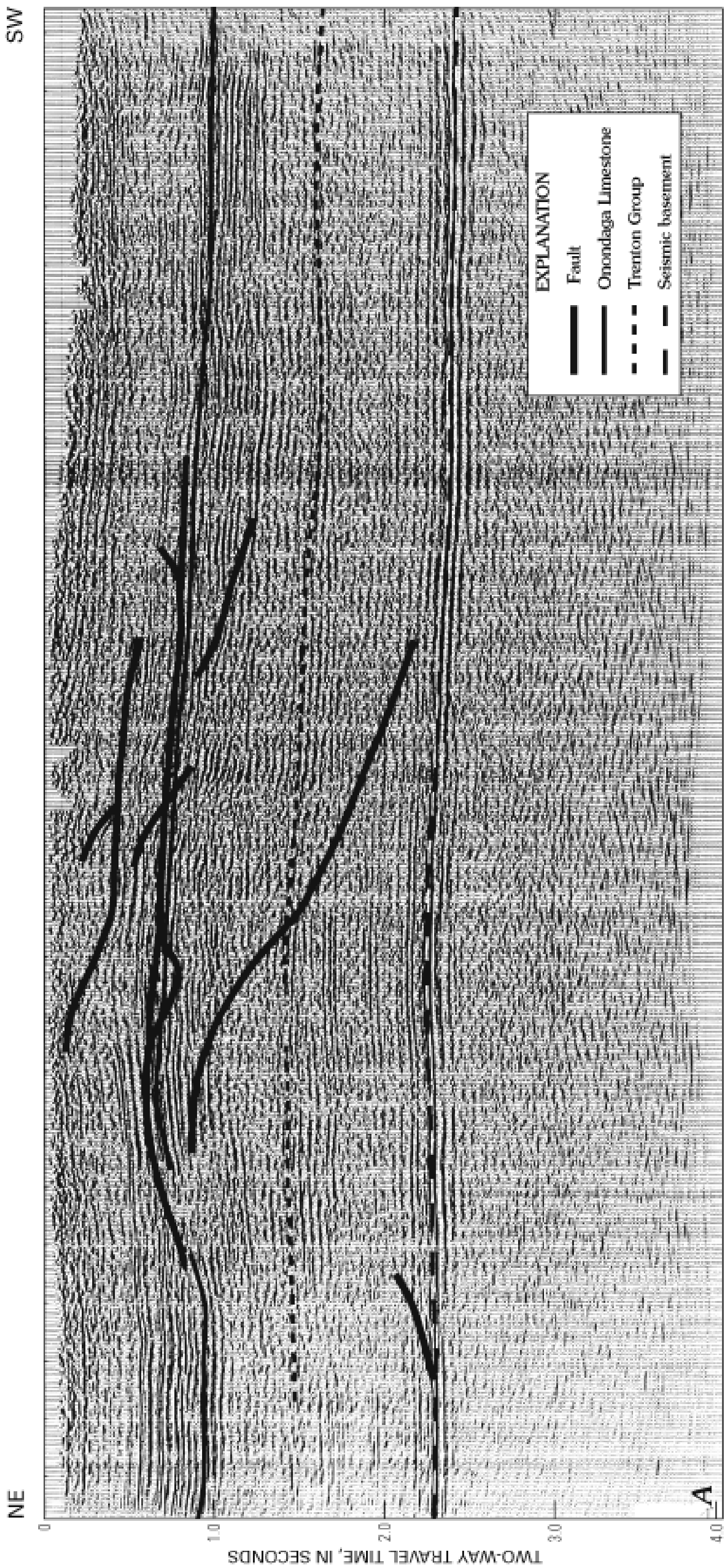



**Figure 21 (above and facing page).** *A*, Strike-line seismic-reflection profile of the Highland County lateral ramp in Virginia. Profile shows seismic data collected along a line approximately 12 mi long. *B*, Same profile as *A* but uninterpreted.

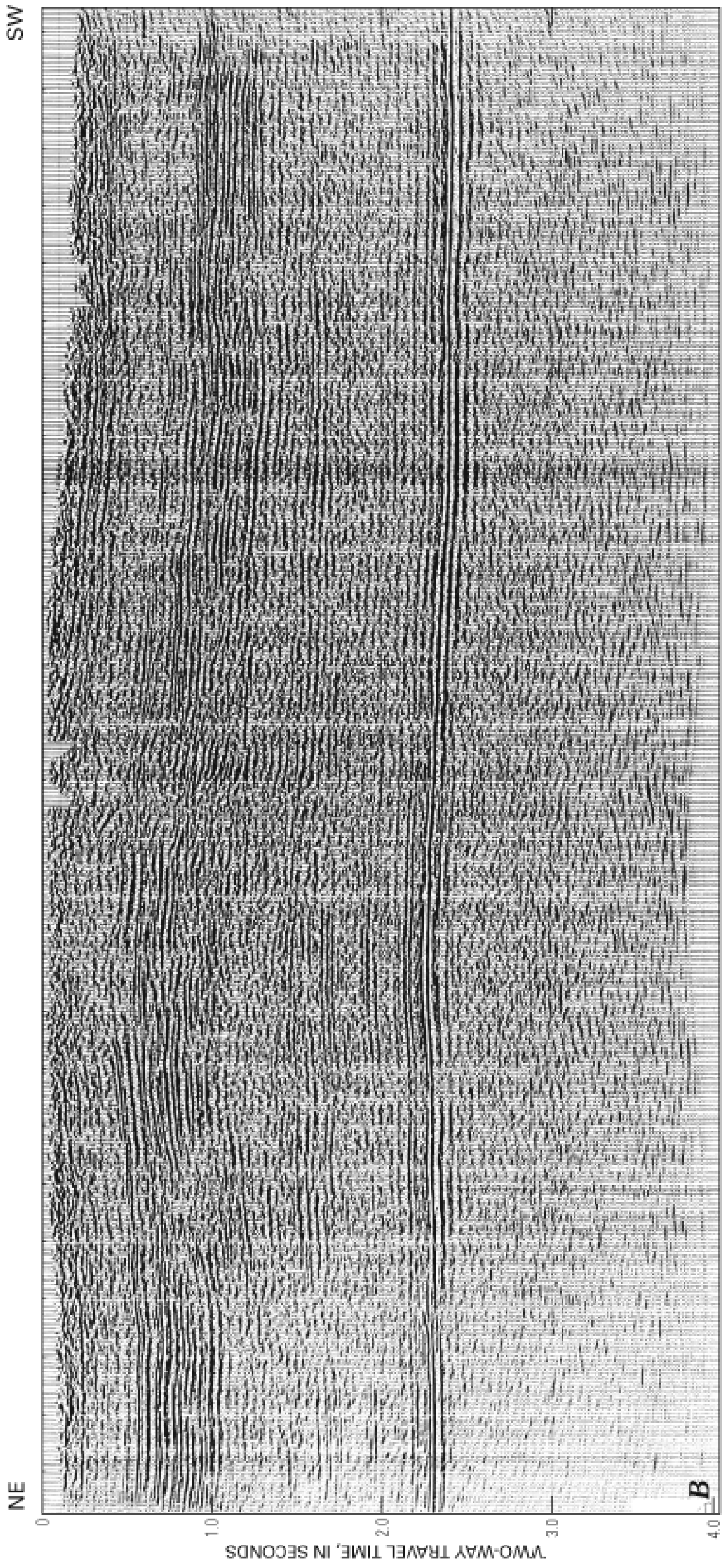



**Figure 21.** Continued.

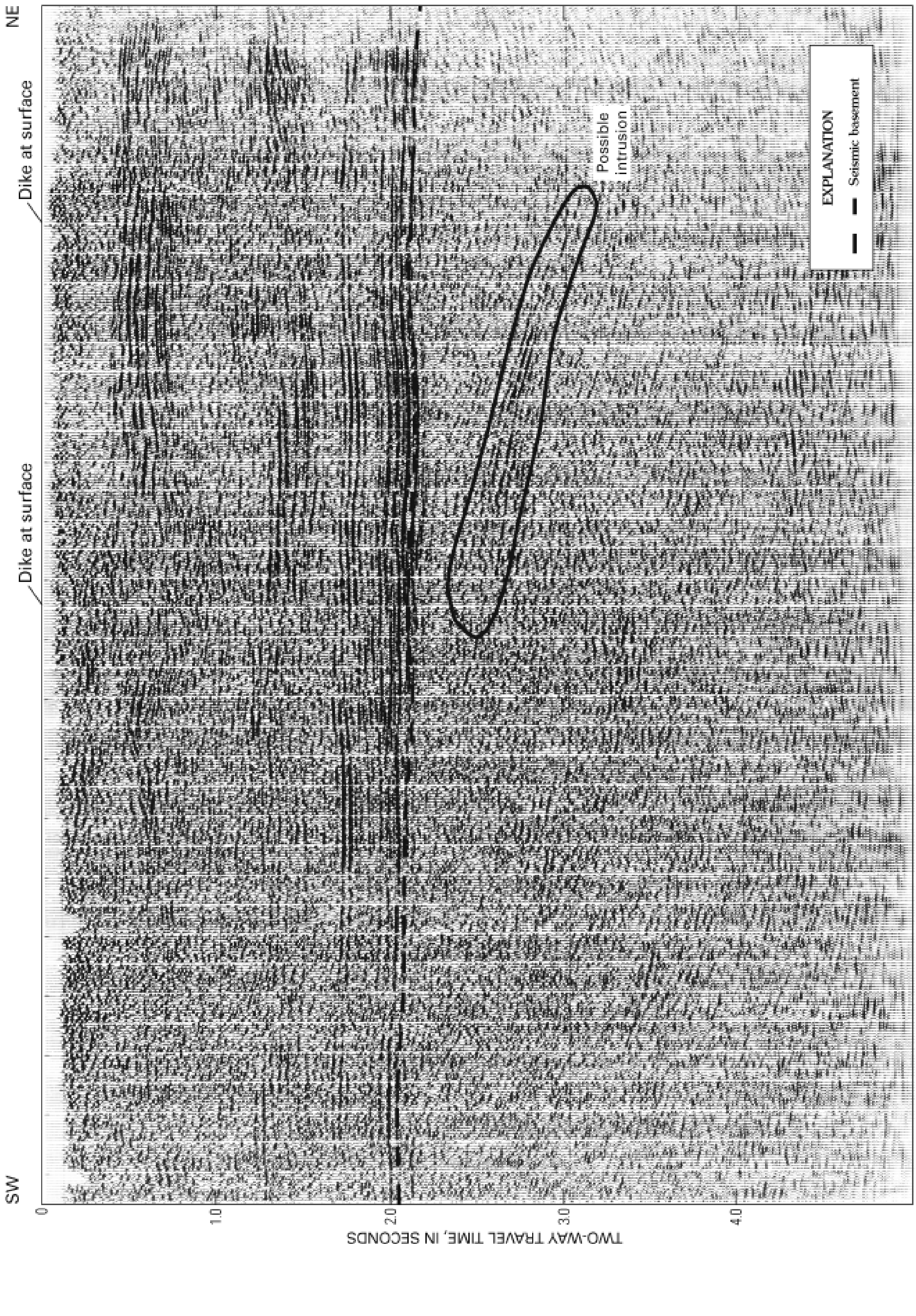



**Figure 22.** Part of a seismic-reflection profile of the western end of the Highland County lateral ramp in Virginia. Profile shows seismic data collected along a line approximately 17 mi long.

Kingsport ramp (which trends N. 73° W.) is most conspicuous in the Blue Ridge and Piedmont rocks and is only weakly expressed in the lower Paleozoic Valley and Ridge rocks; this indicates that the Kingsport ramp may have formed first and that the southern Appalachians, including the Johnson City ramp, pivoted around the Kingsport ramp (fig. 29). In fact, the aeromagnetic map of the United States (Zietz, 1982) shows that the trend of the central Appalachian Blue Ridge province continues into the southern Appalachians. The converse is unlikely to be true because the Kingsport ramp has virtually the same strike as other central Appalachian ramps, whereas the Johnson City ramp is perpendicular to the local strike of the fold belt but is not parallel to the majority of other ramps. The lineament swarm in the Blue Ridge province along the Kingsport ramp may be a still earlier zone of deep basement fracturing that, through reactivation, is manifested in the tectonically superposed and rotated Precambrian and Paleozoic covers. Two distinct directions of probable ramps exist not only here but in at least two other places in the southern Appalachians.

The proposed New River and Blacksburg lateral ramps show the same relationship as the Johnson City and Kingsport ramps. The New River ramp (N. 17° W.) is perpendicular to the local strike of the southern Appalachians. The Blacksburg ramp strikes N. 65° W. Both ramps exhibit fold plunges in the Valley and Ridge province and disruptions in the Blue Ridge province. The trend of the New River in the Valley and Ridge and Appalachian Plateaus provinces is coincident with the New River ramp (hence its name).

B.A. Ferrill and W.A. Thomas (City of Huntsville, Ala., and University of Kentucky, respectively, written commun., 1990) showed an abrupt decrease in thickness of Devonian rocks above the rocks equivalent to the Onondaga Limestone from 3,609 ft east of the New River to 1,641 ft west of the ramp. They also showed an abrupt facies transition from sandstone east of the ramp to shale west of the ramp. Joseph O'Connor (USGS, oral commun., 1990) found an abrupt change across the New River gorge in the sandstones of Pennsylvanian age. To the northeast of the gorge, the sandstones have more rounded grains and have little feldspar present. To the southwest of the gorge, the sandstones have more angular grains, contain more feldspar, and have well-preserved mica flakes. Both of these observations are consistent with the presence of a subaqueous, down-to-the-northeast slope in Devonian through Pennsylvanian time. This slope would have been appropriately positioned to influence the formation of the lateral ramp.

The proposed Knoxville lateral ramp (perpendicular to the local strike) and the Fontana Lake lateral ramp (N. 69° W.) likewise show the same relationships as the two previously illustrated intersecting ramp pairs.

Other lateral ramps with their proposed names are presented in figure 30. The Rising Fawn CSD (cross-strike structural discontinuity), here called the Rising Fawn lateral ramp, was originally named by Thomas and Neathery (1980). Coleman (1988a,b) presented a very thorough discussion of the manifestations of the Rising Fawn CSD (or lateral ramp), including sedimentation, fold plunges, mineral deposits, and modern seismicity.

Two proposed lateral ramps interpreted from the SLAR data neither strike N. 70° W. nor are perpendicular to the local strike of the fold belt. They are here named the Calhoun and Piedmont lateral ramps. The Calhoun ramp connects a series of fold plunges and a 70° change in the local strike of the Valley and Ridge province and projects east-northeastward to the Warwoman lineament (Hatcher, 1974). The Piedmont ramp, farther to the south, connects a pair of apparent left-lateral shear zones (fig. 27, this report).

## LINEAMENT SWARMS OF EASTERN TENNESSEE AND WESTERN NORTH CAROLINA

A swarm of long, throughgoing lineaments can be seen on the SLAR images from eastern Tennessee and western North Carolina (fig. 31). These lineaments range from 31 to more than 217 mi in length. All strike N. 62° to 74° W., with the exception of the lineament that strikes N. 47° W. and passes through Englewood, Tenn. Although these lineaments may not be related to lateral ramps, the coincidence of their strikes with the approximate N. 70° W. direction and their persistence across country without regard to topography or geology make them likely candidates for the usually deeply buried root zones of lateral ramps. Occasional folds plunge out against those lineaments although not in the numbers seen along other ramps described in this report.

## LATERAL RAMPS AND TECTONIC WINDOWS

Tectonic windows are eroded areas of thrust sheets that display the rocks beneath the thrust sheet (Gary and others, 1972). Although the distribution of windows appears to be random, there is a marked coincidence of lateral ramps and tectonic windows, such as the Birmingham window with the Tyrone-Mount Union lateral ramp in Pennsylvania. Inspection of available information suggests that, of the 55 tectonic windows in the central and southern Appalachians, 53 are directly coincident with proposed lateral ramps (fig. 32). The remaining two are along an indistinct, but visible, lineament that can be traced from the Appalachian structural front through the Blue Ridge province. Although no folds plunge out along this lineament, the strike of the lineament is N. 67° W.; therefore, the lineament may be an additional root zone of a lateral ramp.

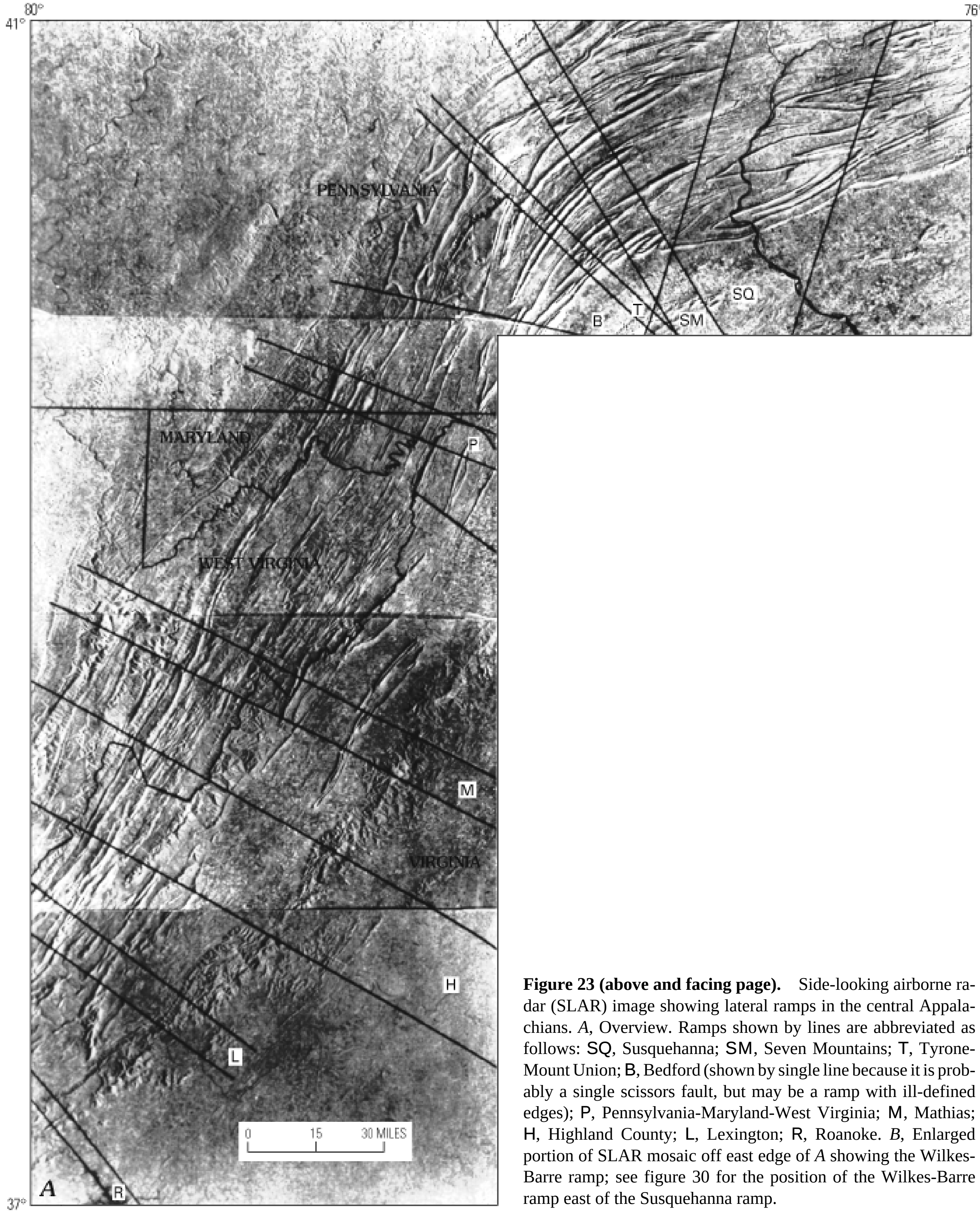



**Figure 23 (above and facing page).** Side-looking airborne radar (SLAR) image showing lateral ramps in the central Appalachians. *A*, Overview. Ramps shown by lines are abbreviated as follows: SQ, Susquehanna; SM, Seven Mountains; T, Tyrone-Mount Union; B, Bedford (shown by single line because it is probably a single scissors fault, but may be a ramp with ill-defined edges); P, Pennsylvania-Maryland-West Virginia; M, Mathias; H, Highland County; L, Lexington; R, Roanoke. *B*, Enlarged portion of SLAR mosaic off east edge of *A* showing the Wilkes-Barre ramp; see figure 30 for the position of the Wilkes-Barre ramp east of the Susquehanna ramp.


**Figure 23.** Continued.

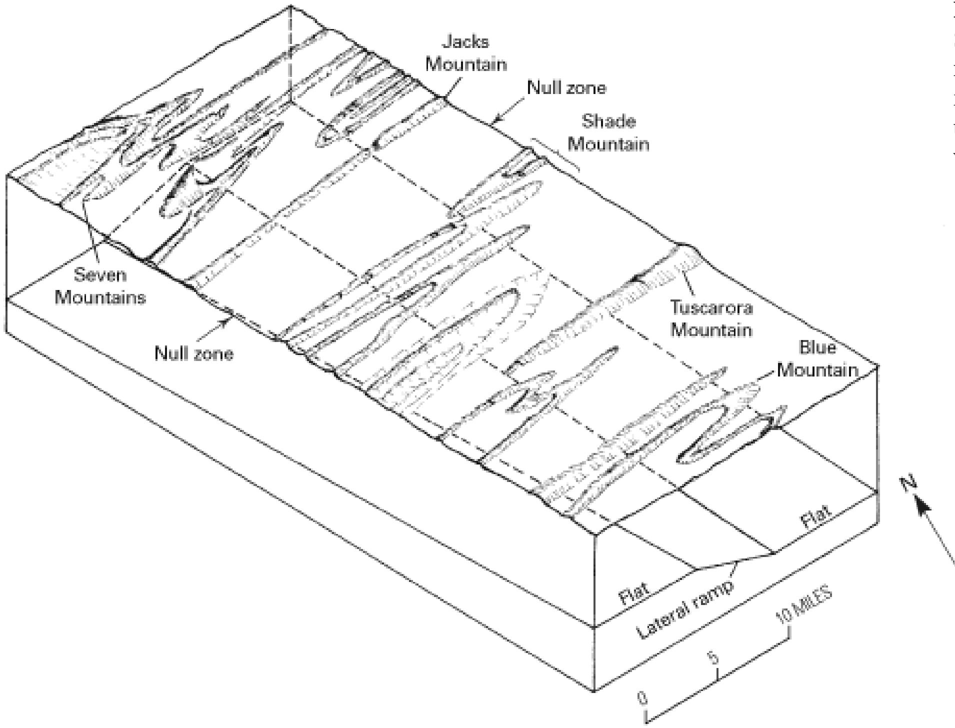
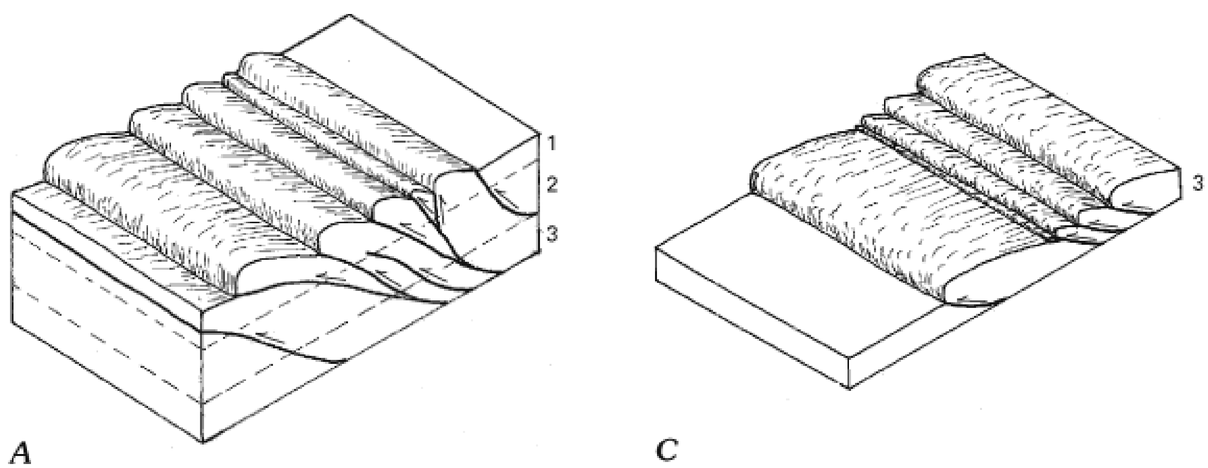



**Figure 24.** Block diagram of the Seven Mountains lateral ramp showing reversal of ramp dips and null zone involving no displacement or hinging under Jacks Mountain, central Pennsylvania.



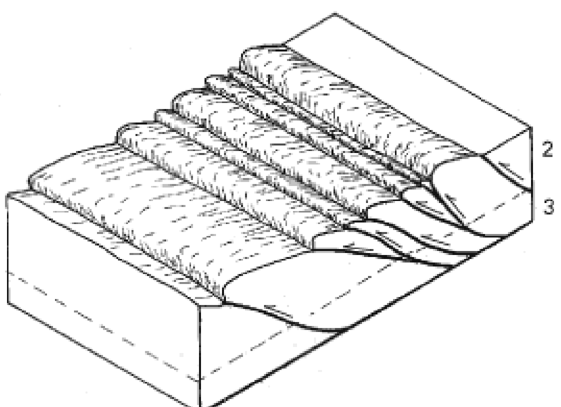




**Figure 25.** Block diagrams showing the concept of fault spacing and fold size relative to height above décollement, or depth of erosion, indicated by numbered erosional levels. *A*, Erosional surface 1 is highest above décollement where folds and faults are few and widely spaced, as in the Valley and Ridge province in central Pennsylvania. *B*, Erosional surface 2 is deeper, or closer to the décollement where folds and faults are more numerous and closely spaced, as in the Valley and Ridge province in Maryland, West Virginia, and Virginia north of the Roanoke lateral ramp. *C*, Erosional surface 3 is closest to the décollement where folds and faults are fewer and more widely spaced, as in the Valley and Ridge province in Virginia south of the Roanoke lateral ramp.

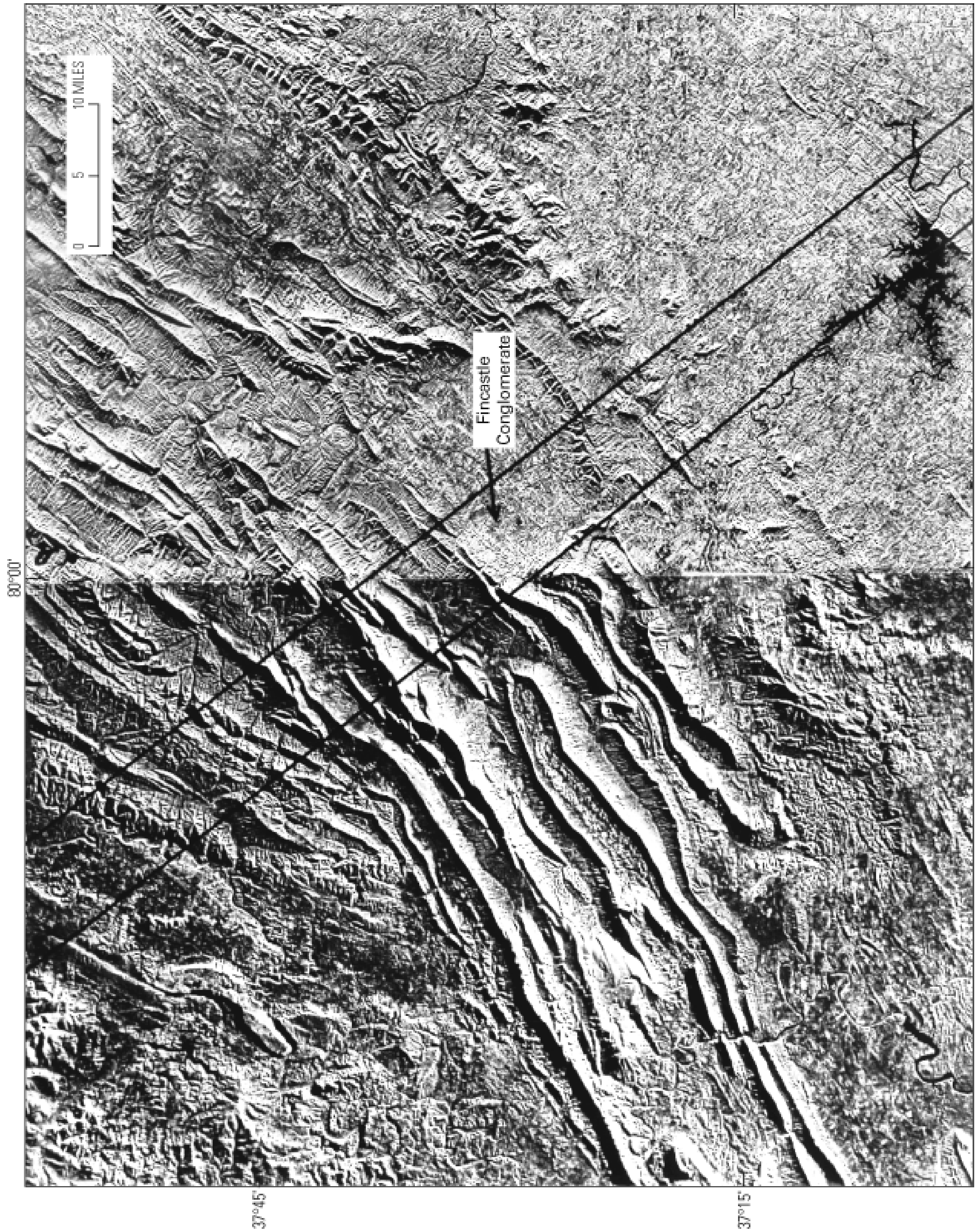



**Figure 26.** Side-looking airborne radar (SLAR) image showing the junction of the central and southern Appalachians along the Roanoke lateral ramp (between parallel lines).

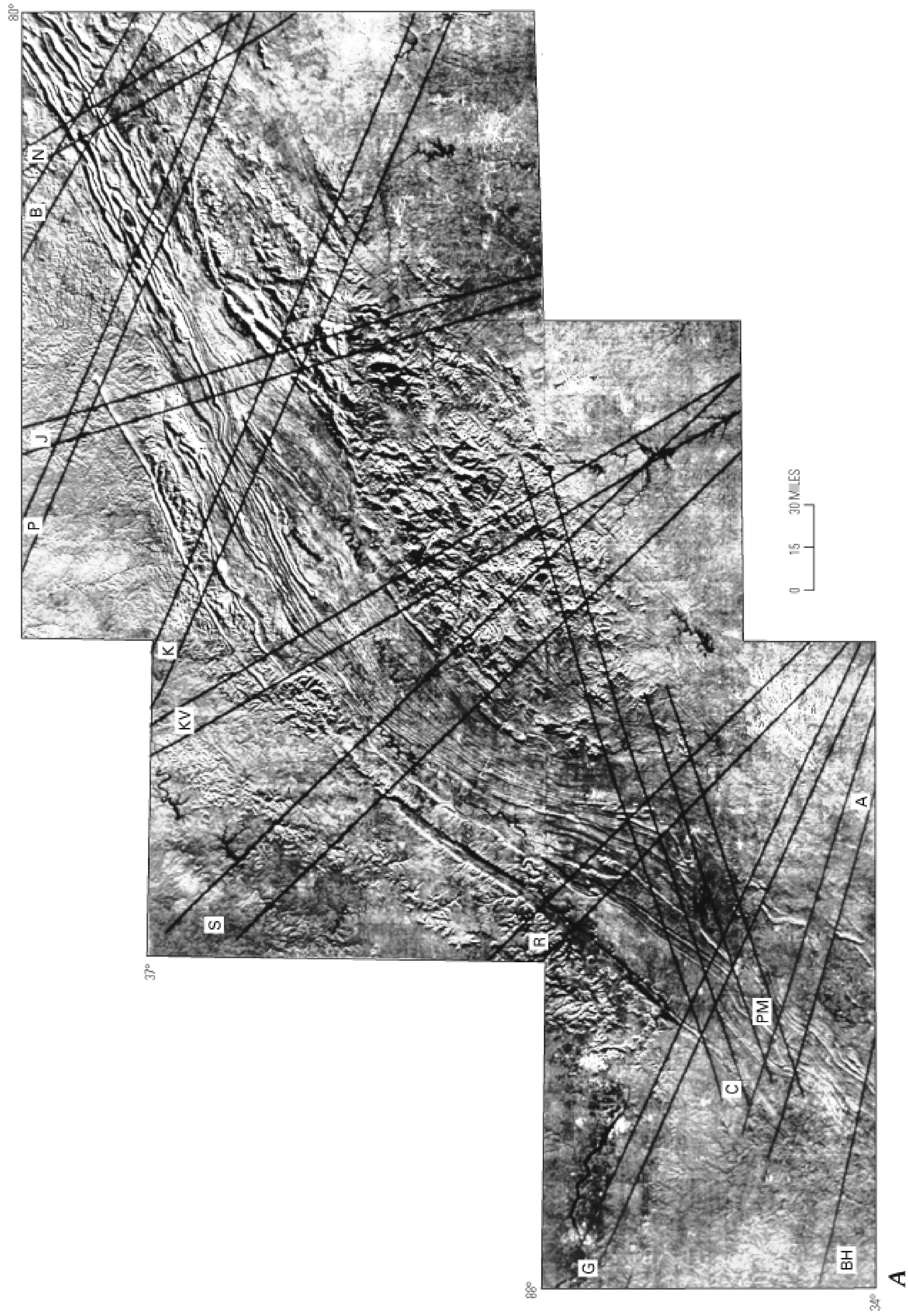



**Figure 27 (above and facing page).** *A*, Side-looking airborne radar (SLAR) composite image of the southern Appalachians showing locations of inferred lateral ramps. Abbreviations are as follows: N, New River; B, Blacksburg; J, Johnson City; P, Pulaski; K, Kingsport; KV, Knoxville; S, Sequatchie Valley; R, Rising Fawn; G, Gadsden; C, Calhoun; PM, Piedmont; A, Anniston; BH, north edge of Birmingham ramp. *B*, Same image as *A* but uninterpreted.

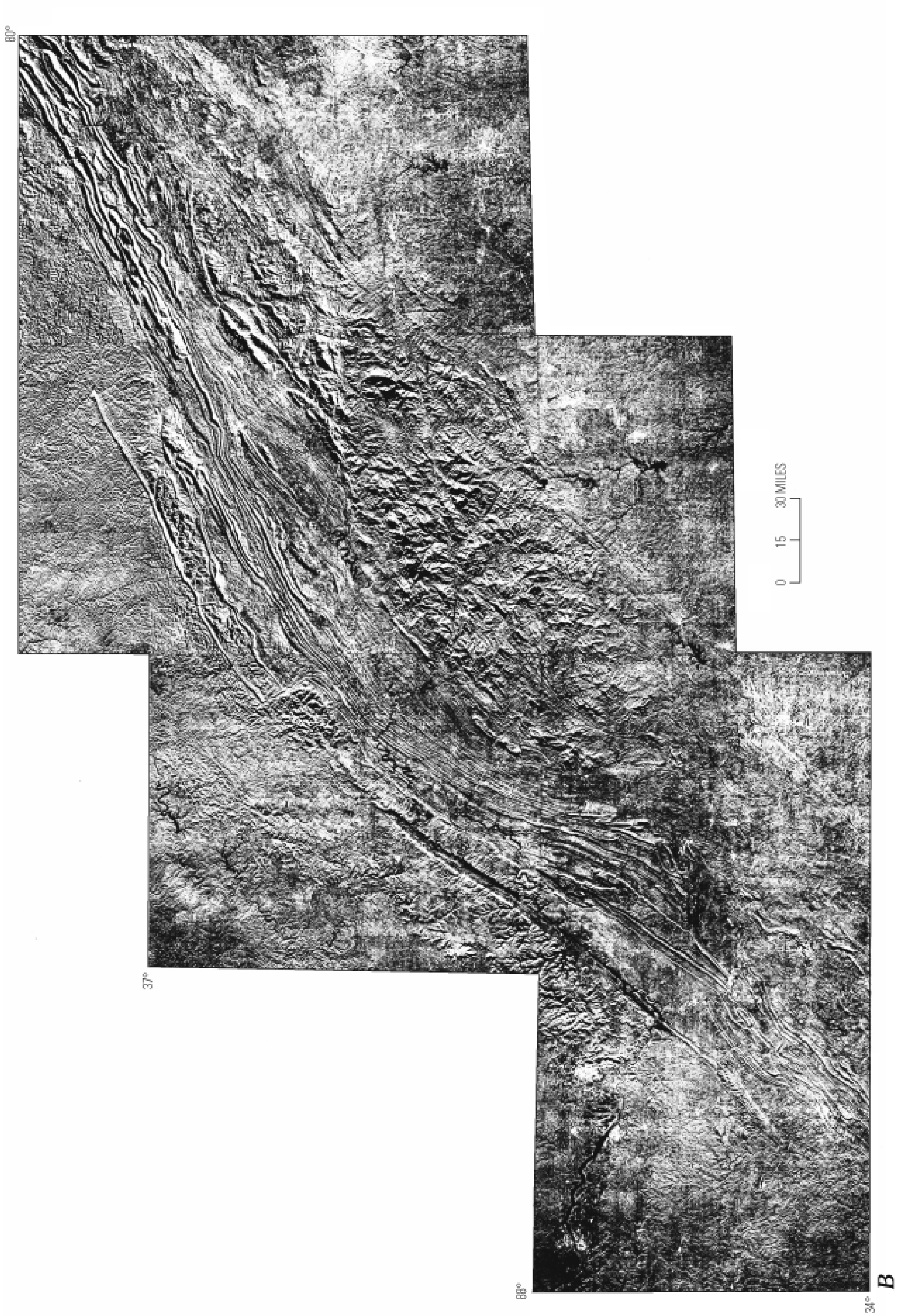



**Figure 27.** Continued.

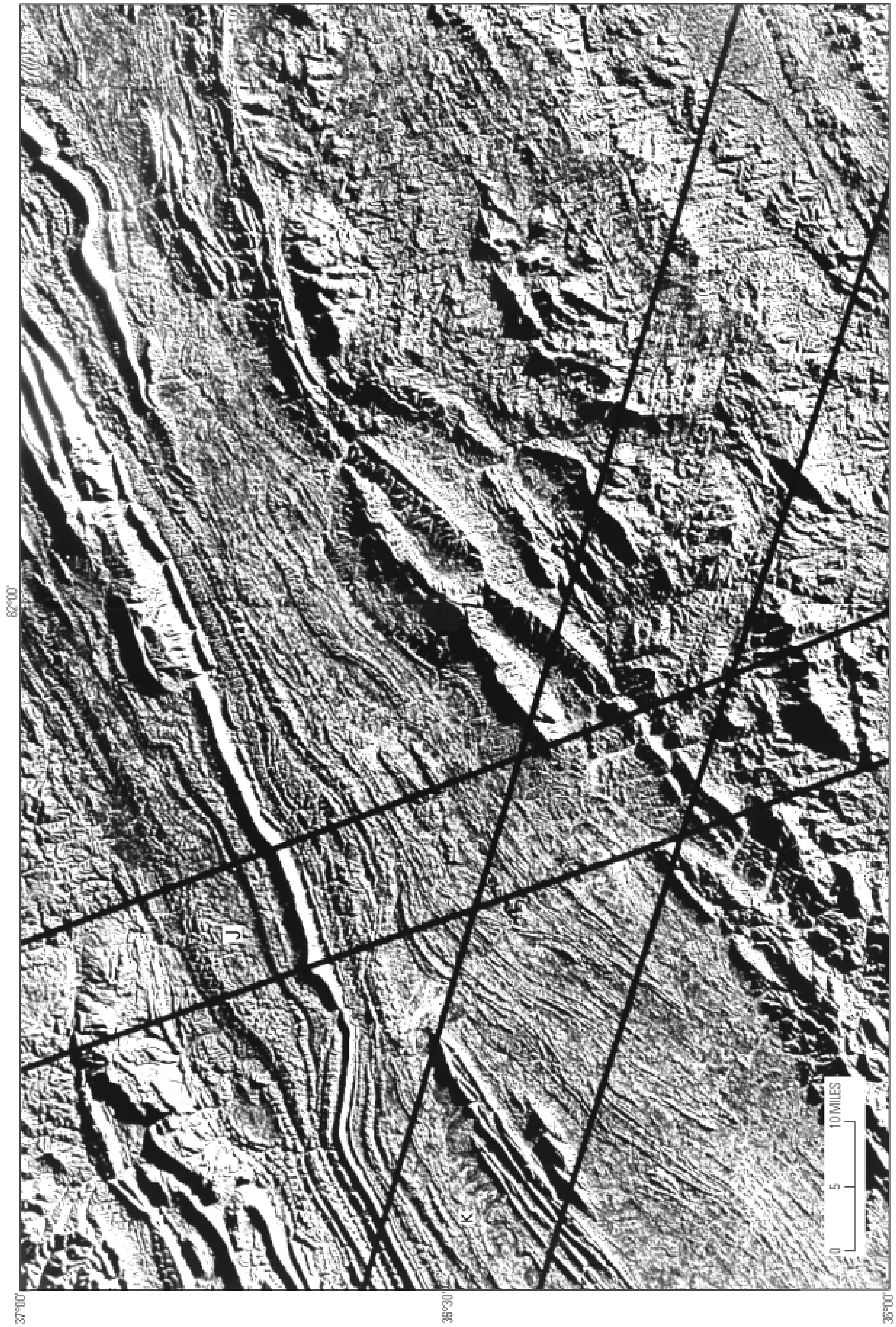



**Figure 28.** Side-looking airborne radar (SLAR) image of parts of the Winston-Salem and Johnson City 1°×2° quadrangles showing the well-defined edges of a lineament swarm striking N. 73° W. and projecting northwestward to plunging fold noses in the Valley and Ridge province. Lateral ramps are abbreviated as follows: J, Johnson City lateral ramp; K, Kingsport lateral ramp.

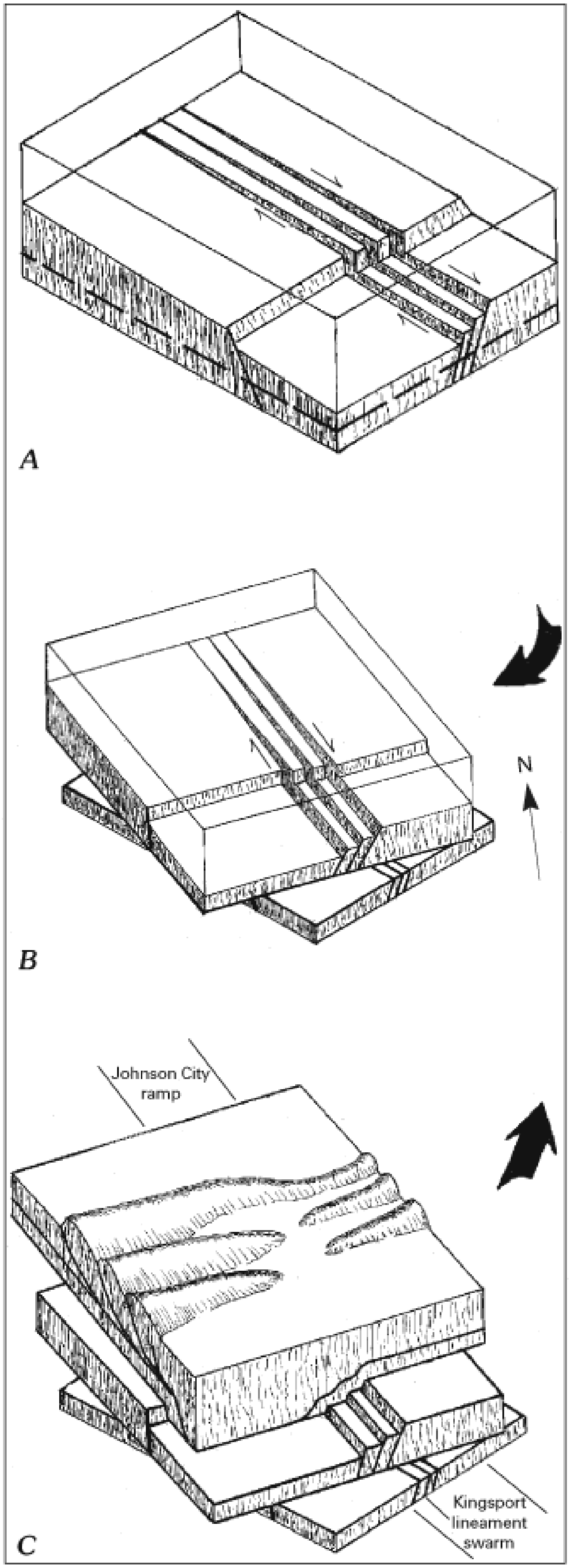



**Figure 29.** Block diagrams showing pivoting and translation of the southern Appalachians around the central Appalachians in the Johnson City, Tenn., area. Arrows show direction of relative movement of upper block. *A*, Strike-slip-faulted basement with future décollement surface shown by heavy dashed line. *B*, Rotation of basement block on décollement surface. *C*, Translation of the basement and cover sequence. Plunging folds developed over the lateral ramp that is, in turn, formed over strike-slip faults. Note that erosion of the cover sequence high above the décollement will leave folded cover rocks in the Valley and Ridge province, but farther south and east in the Blue Ridge or Piedmont province, erosion closer to the décollement will expose the root zone of the basement. The basement strike-slip faults will then appear as lineaments, as near Kingsport, Tenn.

If a tectonic window is present and is the result of a simple eroded thrust fault or duplex structure, then the window manifests itself by a symmetrical, highly elongated geometry. The along-strike dimension is proportional to the adjacent folds (fig. 33*A*). Similarly, if the folds within the duplex structure porpoise slightly, then the windows are symmetrical and have swellings and constrictions along strike (fig. 33*B*).

Conversely, if the window is skewed to the strike of the adjacent folds (fig. 33*C*), or if the window is blunt at one or both ends or is highly asymmetrical (fig. 33*D*), then the geometry demands the presence of a lateral ramp beneath the thrust or duplex structure (fig. 33*C* and *D*). The steepness of the ramp will determine the degree of asymmetry. The structural architecture for the formation of a tectonic window appears to require both a lateral ramp and its intersection with a décollement or its frontal ramp.

From north to south along the Appalachians, as basement becomes shallower and décollements appear at the surface southwest of the Roanoke reentrant, the first major concentration of tectonic windows occurs at the surface. In Tennessee, where numerous décollements are at the surface and lateral ramps are common, tectonic windows also are common. Significantly, in the north-central Appalachians and in the most southerly part of the southern Appalachians where the master décollements are deep, few tectonic windows are present. An examination of figure 18 suggests a probable explanation of this. Structures identical to those that make tectonic windows can be seen in this seismic profile, but the level of erosion would have to be thousands of feet deeper in order to exhume these structures and create these windows.

The three largest tectonic windows (Mountain City, Grandfather Mountain, and Sauratown on figure 32) appear to be considerably larger than the associated hypothesized ramps. A possible explanation is that the windows are partly controlled by lateral ramps that underlie the Blue Ridge as well as by the narrower lateral ramps discussed in this report. The characteristic asymmetry of the windows is consistent with lateral ramp geometry.

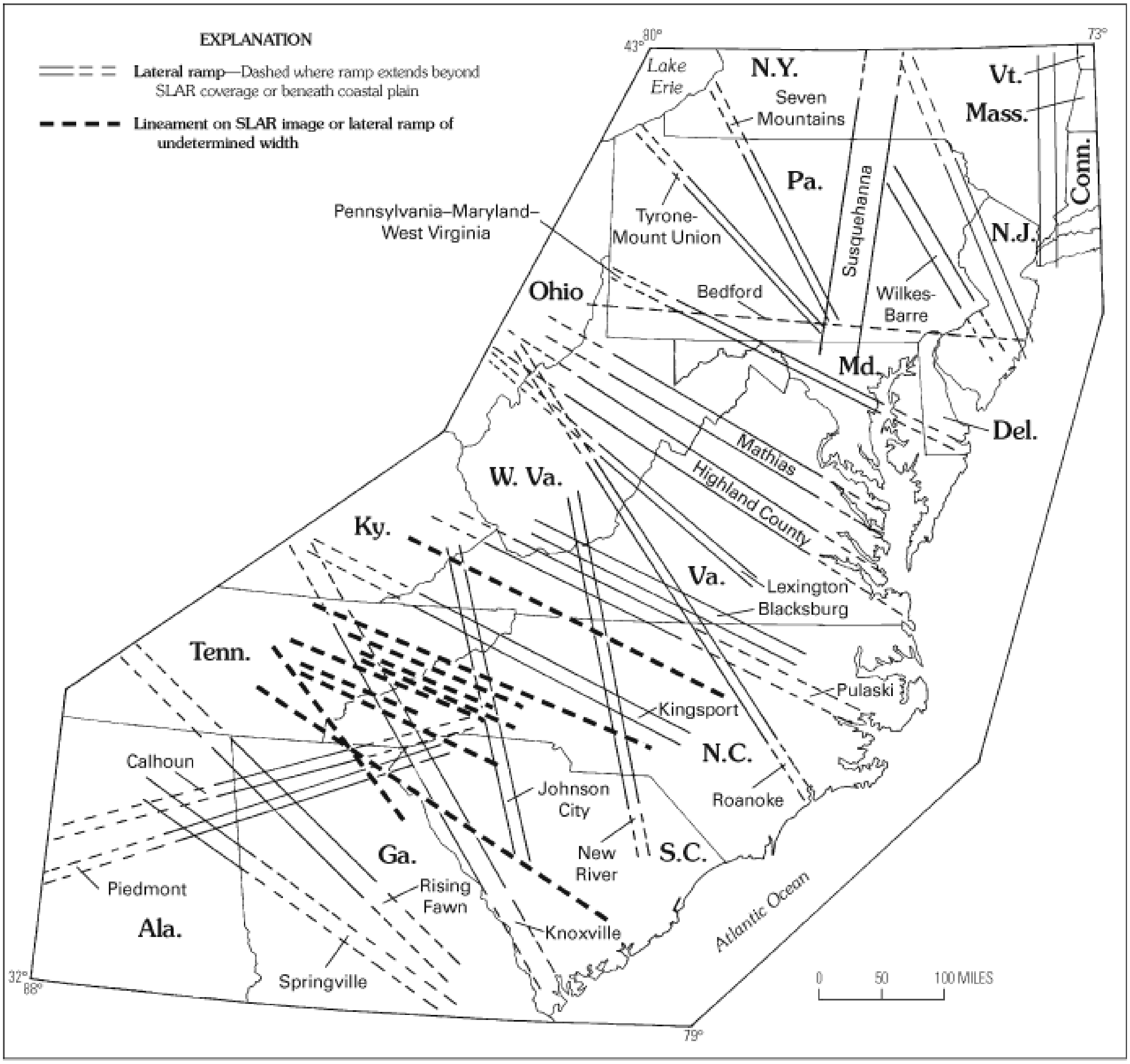



**Figure 30.** Map showing location of selected lateral ramps in the central and southern Appalachians. Bedford ramp and extensions of other ramps shown by light dashed lines. Two lateral ramps in the northeast corner of the map are in the northern Appalachians and are unnamed. Note the lineament swarms, represented by single heavy dashed lines, that more or less parallel some ramp lines in the southern half.

## LATERAL RAMPS AND FREQUENCY OF DISTURBED ZONES

Disturbed zones (fig. 34) are sequences of severely thrust faulted and folded rocks either in the hanging walls or footwalls adjacent to thrust faults or between closely spaced pairs of thrust faults (Pohn and Purdy, 1982, 1988; Pohn and others, 1985). Most areas where there are numerous disturbed zones lie either along the margins of, or directly over, lateral ramps. Repeated stick-slip movement over the lateral ramps during the Alleghanian orogeny probably caused an increase in faulting associated with the lateral ramps. The highest frequency of disturbed zones (40) is directly over the Roanoke lateral ramp, probably one of the most highly displaced and definitely the most rotated of any of the lateral ramps in the Appalachians.

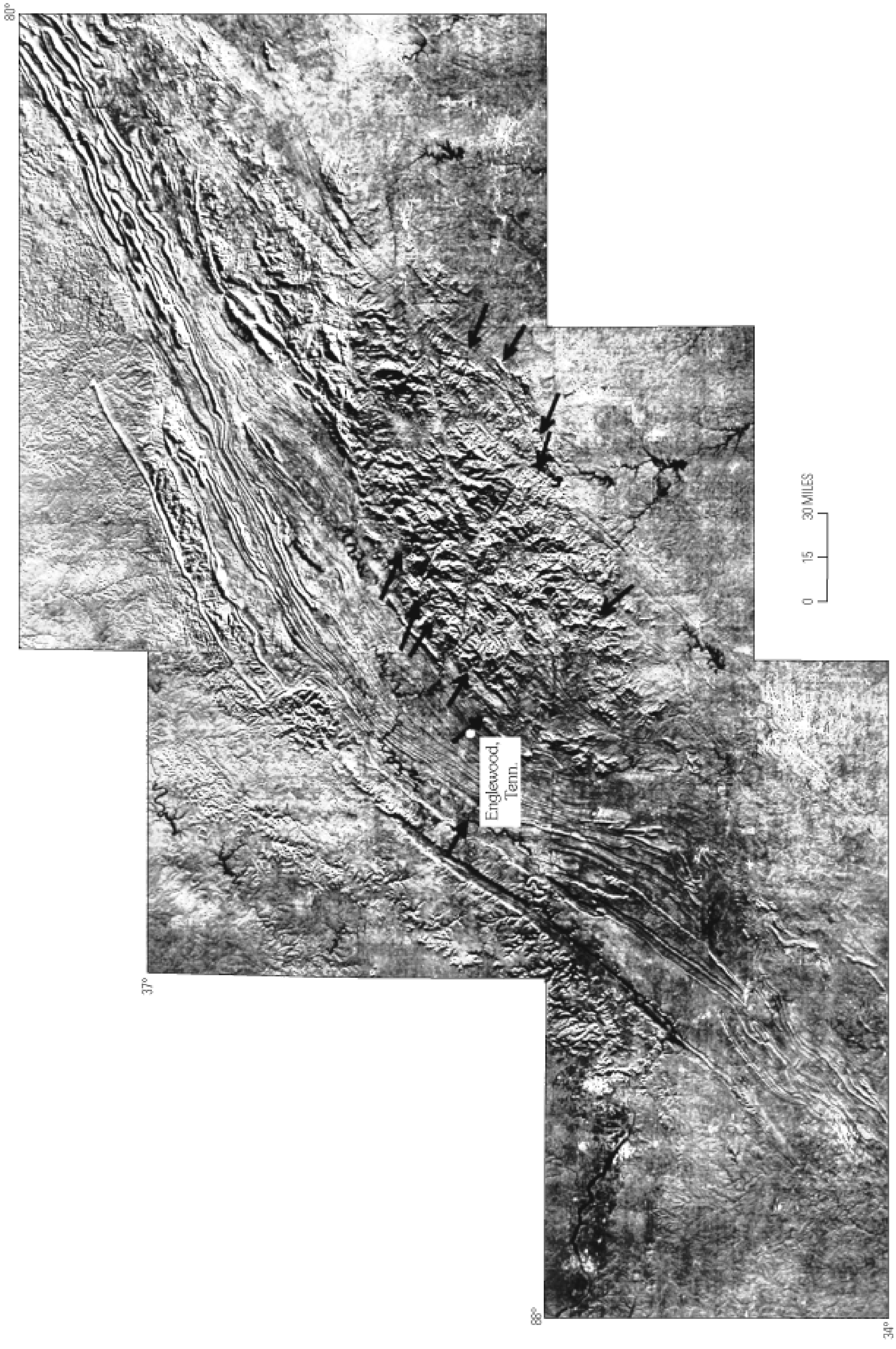



**Figure 31.** Side-looking airborne radar (SLAR) image of the southern Appalachians. Arrows indicate lineament swarm in western North Carolina and eastern Tennessee. This is the same image shown in figure 2.

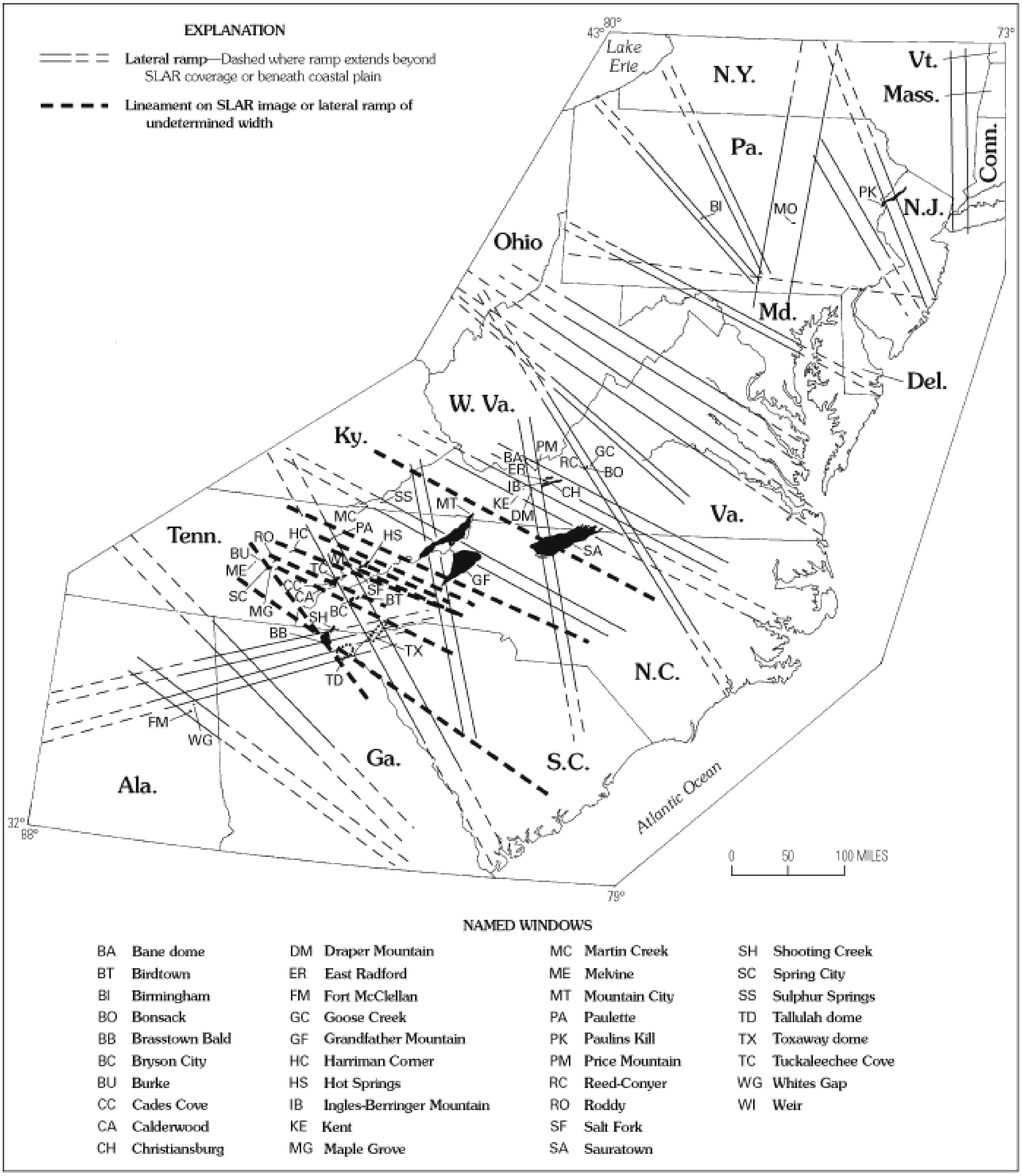



**Figure 32.** Map showing the relationship between lateral ramps, lineaments, and tectonic windows in the central and southern Appalachians. See figure 30 for ramp names. Named windows are listed above. MO, unnamed window encompassed by part of Mauchono fault of Wood and Bergin (1970). Unlabeled windows are unnamed in the literature. Toxaway and Tallulah domes are shown by dashed lines to reflect uncertainty as to whether or not they are true windows.

## LATERAL RAMPS AND POSSIBLE BASEMENT FAULTING

With the exception of the Bedford lateral ramp, no direct evidence connects lateral ramps to faults in the underlying basement; there is, however, some inferential evidence for many of the proposed ramps. Table 1 shows that six ramps have swarms of igneous intrusions above the ramps; the Mathias ramp may also have swarms of intrusions above it. Moreover, these swarms are parallel to the lateral ramps.

Table 1 shows that all but three proposed ramps (Seven Mountains, Bedford, and Lexington) have a high frequency of modern earthquakes coincident with them (see the following section). In fact, the Bedford ramp shows the presence of a flower structure in the basement directly beneath the ramps (James Farley, petroleum consultant, oral commun., 1985). This evidence, coupled with the fact that there are mapped faults at the surface along the whole of the Bedford ramp, indicates that the Bedford ramp probably has a direct connection to basement. This does not imply a direct connection between basement and the superjacent lateral ramp in all cases but does imply that movement in the basement (probably strike-slip) caused differential compression without accompanying cross-strike failure in the cover rocks. This differential movement in the cover rocks, accompanied by a differential cumulative thickness on either side of the lateral ramp, is responsible for the conspicuous change in wavelength of folds along strike.

Unfortunately, seismic-reflection profiles, the most important source of evidence, do not show any obvious

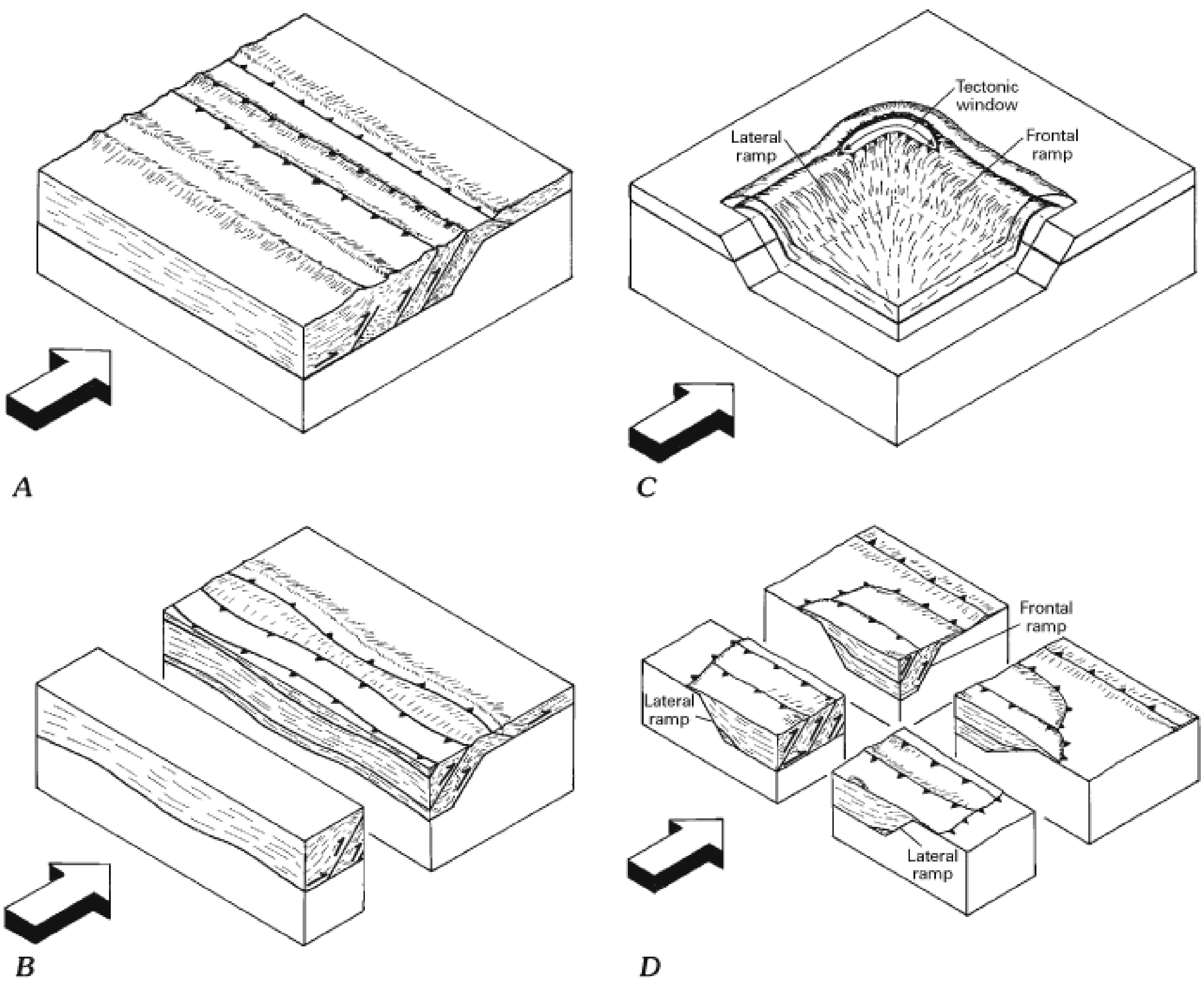



**Figure 33.** Block diagrams showing different geometries of thrust faults that result in the formation of tectonic windows. Teeth are on upper plate of thrust fault; small arrows show fault movement sense. *A*, Tectonic window formed by erosion of a simple duplex. *B*, Tectonic window formed by erosion of a slightly warped or undulating duplex. *C*, Skewed tectonic window exposed by erosion near the intersection of a lateral ramp and a frontal ramp. *D*, Blunt-ended tectonic window formed from a pair of lateral ramps.

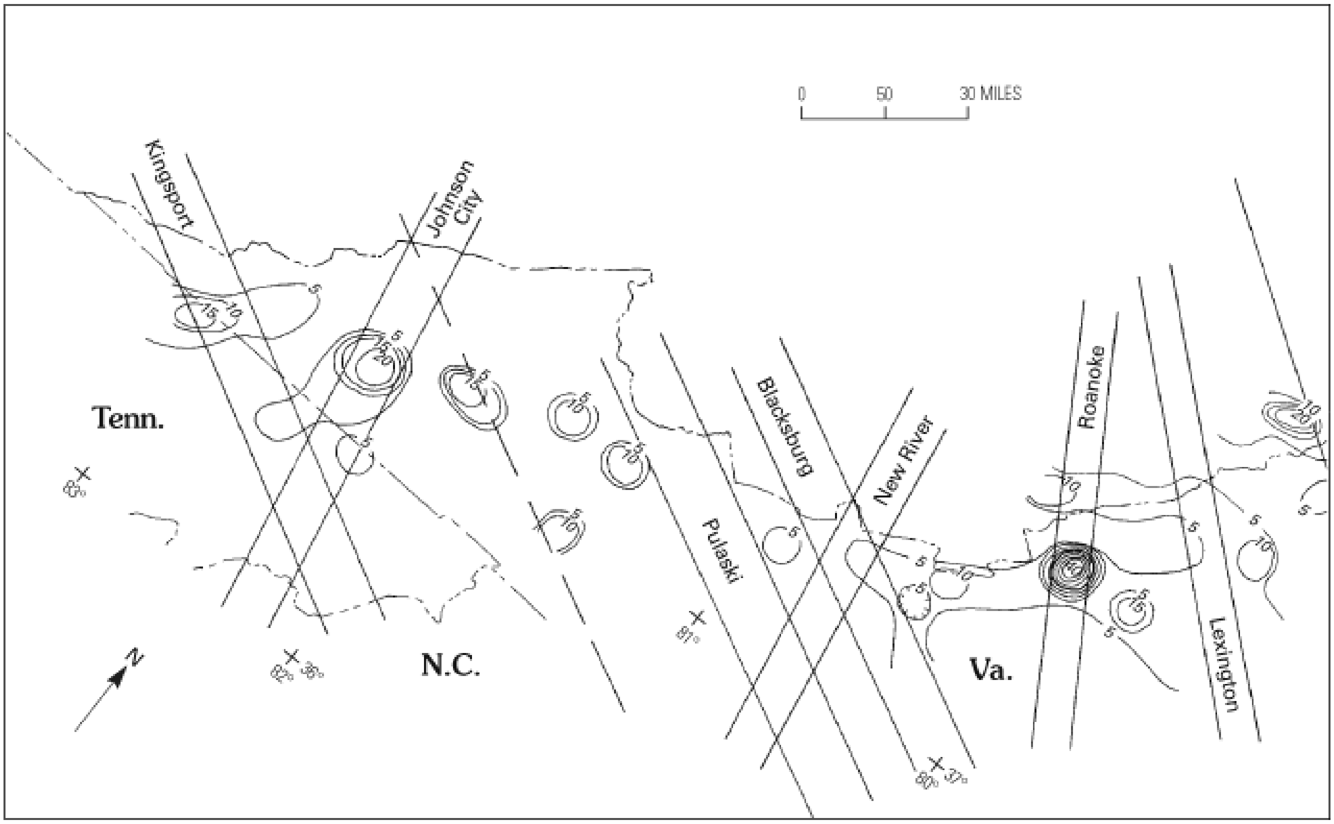



**Figure 34 (above and facing page).** Map showing contoured frequency of severely thrust faulted and folded (disturbed) zones observed in the field, per 7.5-minute quadrangle in relation to inferred lateral ramps in the central Appalachians. Contour interval is 5 disturbed zones. Hachures indicate closed area of fewer disturbed zones. Note peak frequency of 40 disturbed zones centered over the Roanoke lateral ramp. Single dashed line in southwestern Virginia marks major lineament parallel to ramps; there is not enough information to define both sides of the suspected ramp.

faults in the basement. This lack of data is partly due to the fact that most hydrocarbon exploration companies generally do not run strike-line seismic profiles. Even if there were many more strike-line profiles, basement strike-slip faults would be unlikely to show unless there was a significant velocity contrast across the fault. In addition, if the faults were active with pure strike-slip motion, then there would be little or no topographic relief on the fault. Coleman (1988b) illustrated seismic evidence for basement offset beneath the Anniston lateral ramp and cited nonseismic geophysical evidence for basement offset beneath other similar features.

## MOVEMENT ALONG LATERAL RAMPS THROUGH TIME

Proprietary seismic-reflection data show that along-strike basement faults were active as growth faults from Precambrian until at least Middle Ordovician time. Cross-strike faults also were at least intermittently active for this same period of time. Activity on the cross-strike faults does not appear to have continued past Middle Ordovician time. A map showing the relationship between Mesozoic basins and lateral ramps in the central and southern Appalachians (fig. 35) shows that horst blocks of Precambrian rocks crossing the basins, narrowing of the basins, and east-west border faults all occur over eastward extensions of many of the proposed lateral ramps. In addition, Mesozoic intrusions are coincident with at least six of the lateral ramps. Continued reactivation until the present is strongly indicated by the presence of Eocene intrusions along the Highland County lateral ramp and by the observation that more than 48.7 percent of modern earthquakes since 1628 (Earth Technology Corporation, written commun., 1984) are directly coincident with lateral ramp positions (fig. 36). This is in spite of the fact that lateral ramps occupy no more than 15 percent of the geographic area in the central and southern Appalachians.

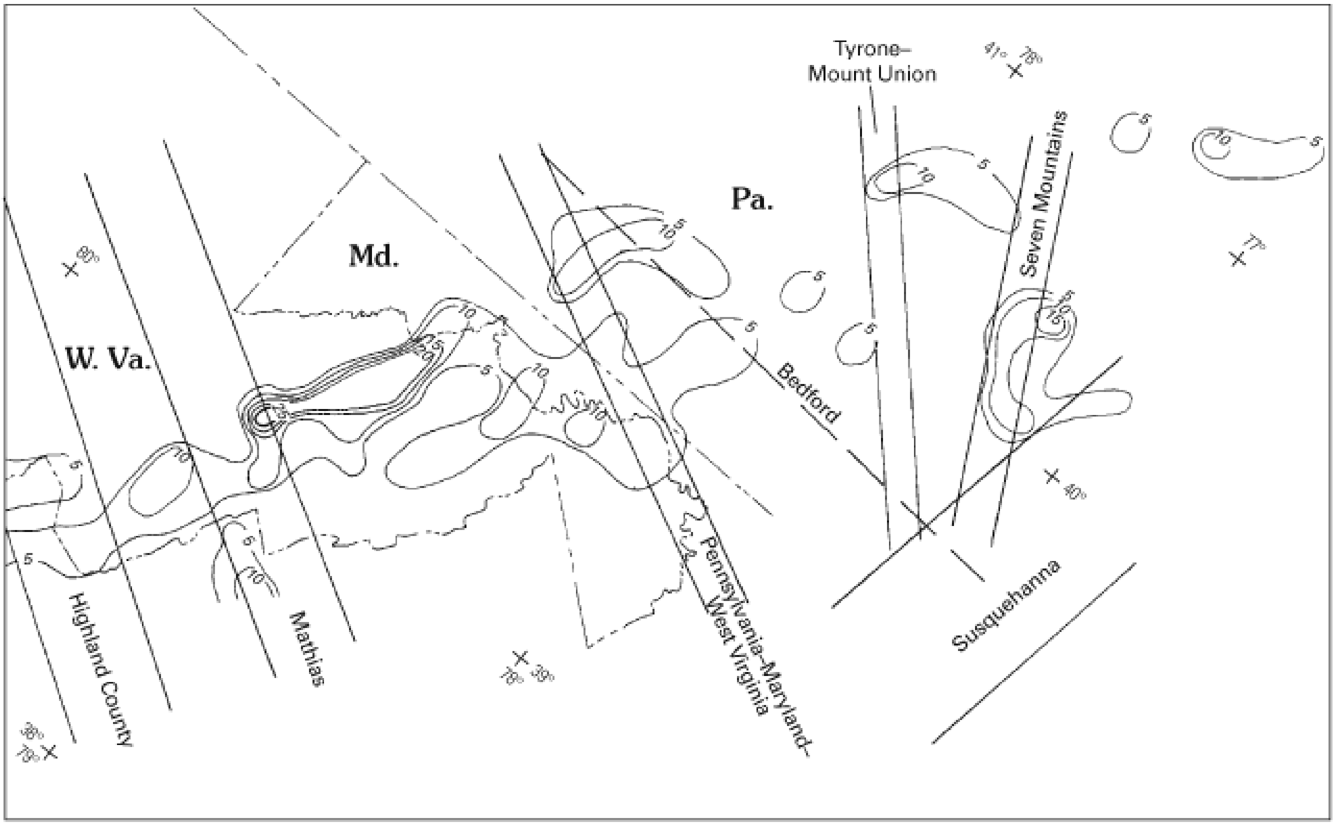



**Figure 34.** Continued.

## OBSERVED ASSOCIATION OF LATERAL RAMPS AND GIANT LANDSLIDES

Schultz (1986) and Schultz and Southworth (1989) have reported on giant, ancient landslides in the central and southern Appalachians. Some of these landslides are mile-sized blocks that are tens to hundreds of feet thick and probably are the largest landslide blocks east of the Great Plains. Each of these landslides either is directly on a lateral ramp or is between two closely spaced lateral ramps. Although the landslides have no direct connection to the lateral ramps, the high frequency of earthquakes coincident with the lateral ramps suggests that earthquakes may have acted as triggering mechanisms for the landslides (see the sections above "Lateral Ramps and Possible Basement Faulting" and "Movement Along Lateral Ramps Through Time").

## POSSIBLE RELATIONSHIP OF LATERAL RAMPS TO OFFSHORE TRANSFORM FAULTS

A map of lateral ramps in the central and southern Appalachians shows that nearly two-thirds of the postulated ramps have strikes of N. 60° to 70° W. This direction is the same as the strike of most of the transform faults mapped offshore (Schouten and Klitgord, 1977) (fig. 37*A*). In fact, extending the lateral ramp zones offshore produces an alignment of two ramps with transform fault zones. Perhaps more significant is the observation that the spacing of the continental ramps and the spacing of the oceanic transform faults are very similar, but the two appear to be offset left laterally 25 mi from one another. Removal of that offset brings the two sets into direct alignment in both strike and spacing (fig. 37*B*). This "coincidence" appears to be too fortuitous to be truly coincidental. This suspected major strike-slip movement, along with similar strike-slip movement on

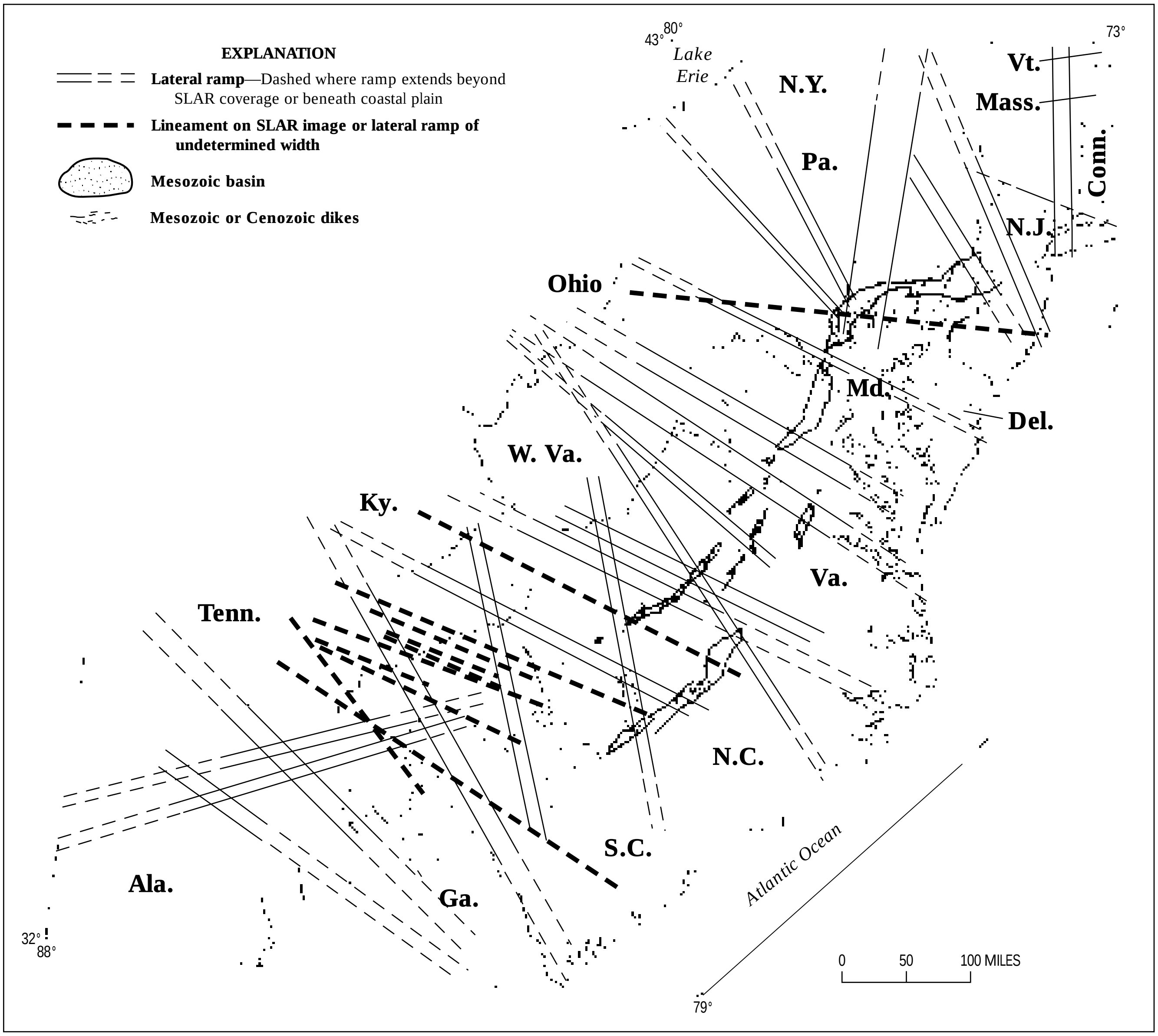



**Figure 35.** Map showing relationship among lateral ramps, Mesozoic basins, and associated Mesozoic and Cenozoic dikes in the central and southern Appalachians. See figure 30 for ramp names.

major continental structures like the Brevard fault zone, probably occurred as the Alleghanian orogeny ceased.

A reactivated fundamental fracture system extended offshore as the North American and African continents separated during episodes of sea-floor spreading to produce transform faults in the new oceanic crust. This same fracture system was, during earlier times of compression, responsible for the formation of lateral ramps in the overlying cover rocks (fig. 38).

## THE PRESENCE OF LATERAL RAMPS WORLDWIDE

Examination of Landsat and SLAR images of major fold-and-thrust belts shows that, of the three main lateral-ramp recognition criteria, the two that can be identified photogeologically (narrowing or plunging out of fold noses across an entire fold-and-thrust belt and long, straight river

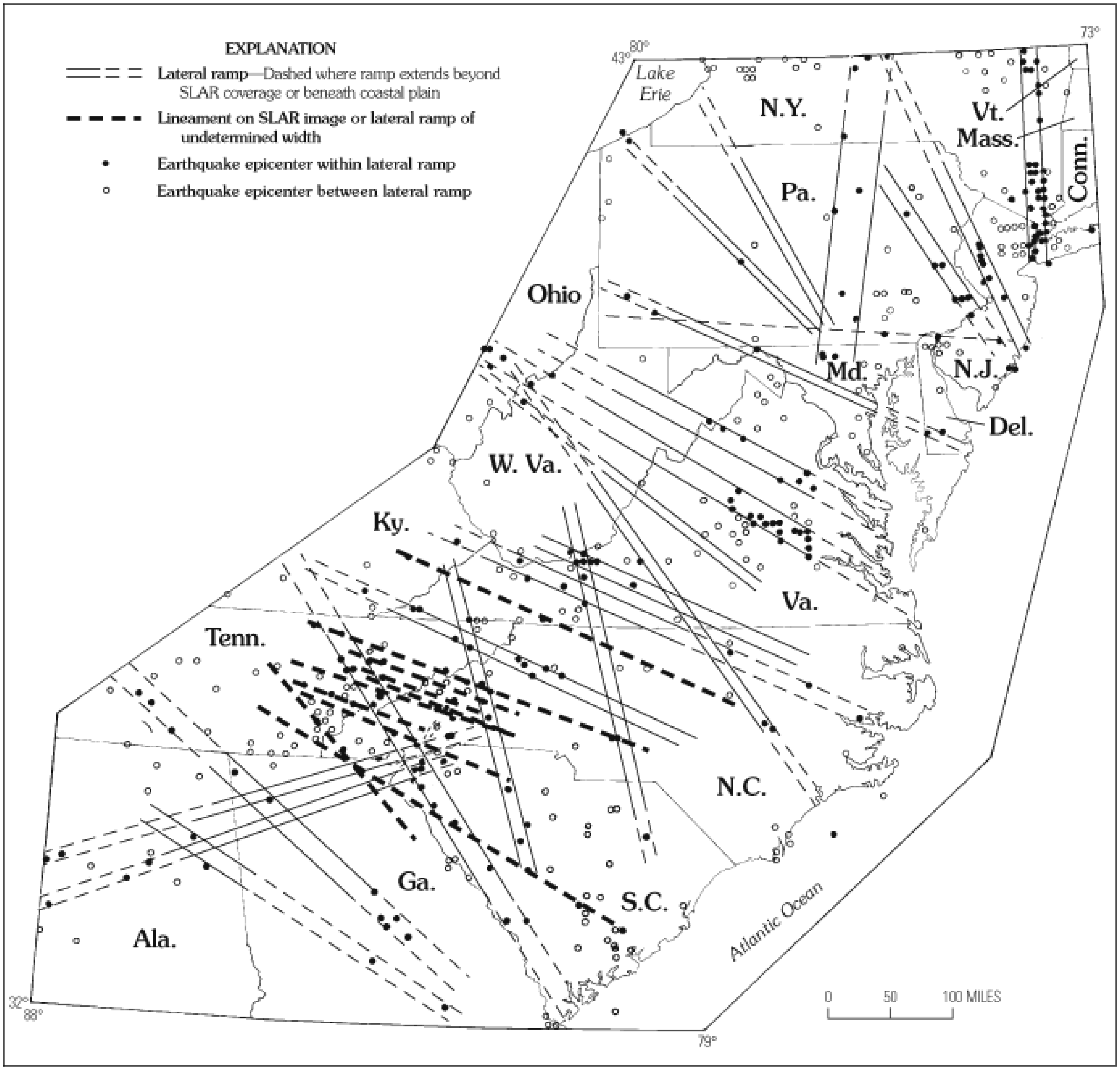



**Figure 36.** Map showing relationship between lateral ramps and earthquakes in the eastern United States. See figure 30 for ramp names. Earthquake data are from Earth Technology Corporation (written commun., 1984). Modified from Pohn and Coleman (1991).

segments crossing a fold belt) are present in almost every instance. Probable lateral ramps were identified on SLAR and Landsat images of the following regions: the Ouachita Mountains of Arkansas; the Rocky Mountains; Morocco, south of the Anti-Atlas Mountains; western Yugoslavia in the Dinaric Alps; the Brooks Range of Alaska, where they are associated with tectonic windows; Papua New Guinea; China; and numerous other fold-and-thrust belts. In addition, J.L. Coleman, Jr. (Amoco Production Company, oral commun., 1990), has seen both lateral ramps and associated adjacent tectonic windows at Semail Gap in Oman. Three of these examples are presented in more detail below.

A review of publicly available data from fold-and-thrust belts around the world reveals that surface indicators of lateral ramps are present in every belt examined to date. The surface expressions of these lateral ramps are easily discernible on images from both spacecraft and aircraft. When other geophysical data, such as seismic-reflection profiles, become available, they probably will reveal additional information on the detailed nature of lateral ramps—a fundamental aspect of fold-and-thrust-belt architecture.

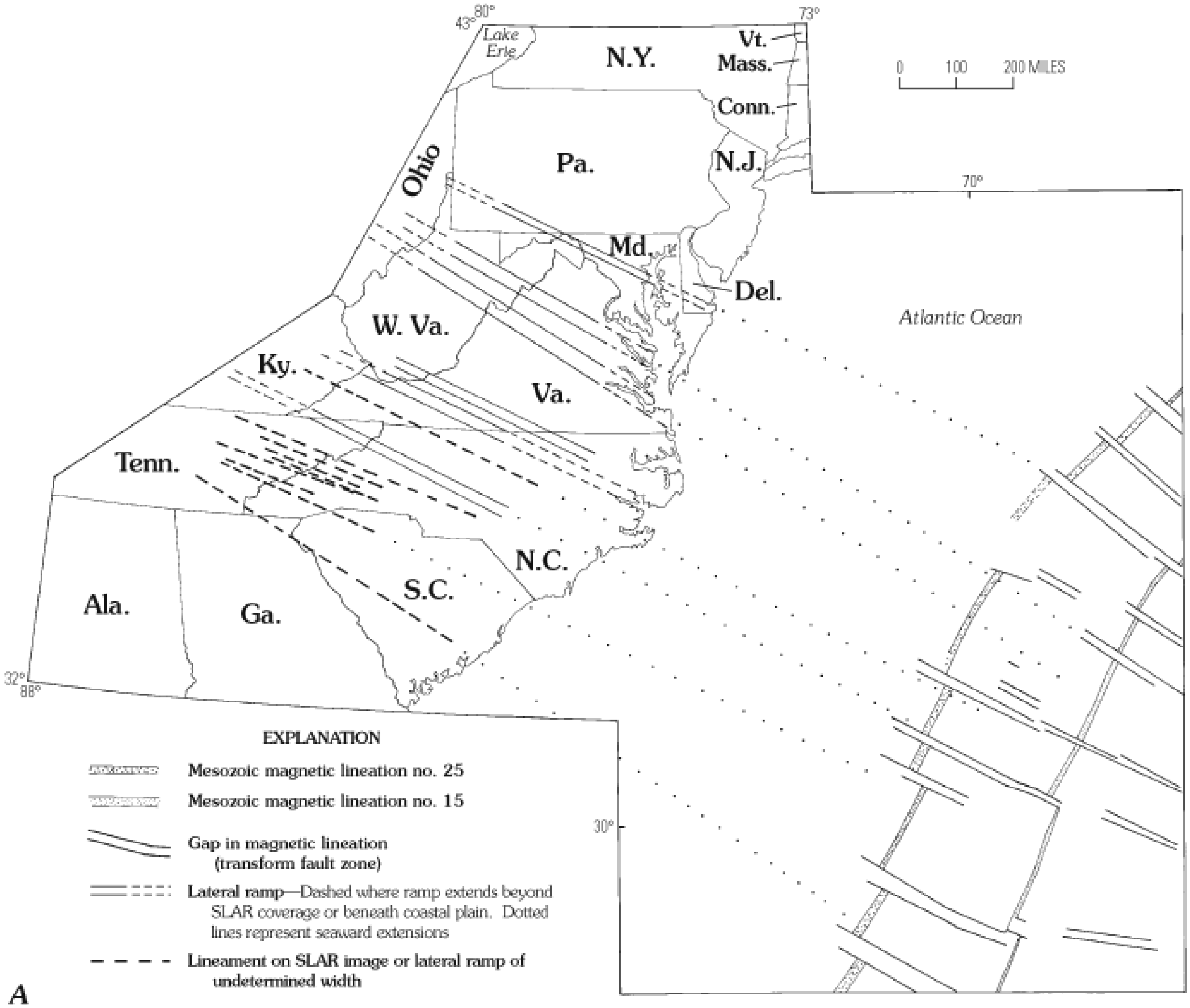



**Figure 37 (above and facing page).** *A,* Map showing relationship between lateral ramps and major N. 60°–70° W.-trending lineament zones in the central and southern Appalachians and transform faults offshore (transform faults modified from Schouten and Klitgord, 1977). The transform faults are expressed as gaps in the positive magnetic sea-floor spreading lineations. Only two positive magnetic sea-floor-spreading lineation zones (nos. 15 and 25; Schouten and Klitgord, 1977) are represented. *B,* Same as *A* but with 25 mi left-lateral movement. Because of the left-lateral movement, latitude and longitude are not shown.

## LATERAL RAMPS IN THE BROOKS RANGE, ALASKA

The Brooks Range crosses the entire width of Alaska from approximately lat 68° to lat 70° N. Like the Appalachians, the Brooks Range is a fold-and-thrust belt where folds are conspicuous because of the presence of erosionally resistant units. However, unlike the Valley and Ridge province where both synclines and anticlines are apparent, in the Brooks Range foothills, only the synclines are conspicuous. This circumstance is similar to that of the Appalachian Plateaus province; in fact, the Brooks Range foothills appear to represent a tectonic regime similar to that of the Appalachian Plateaus.

SLAR images of the western Brooks Range were obtained by the USGS in 1980. The radar images, which include both north-looking and south-looking directions, are mosaics of the Point Hope, De Long Mountains, Misheguk Mountain, Howard Pass, Point Lay, Utukok River, Lookout Ridge, and Ikpikpuk River 1°×2° quadrangles (fig. 39*A*).

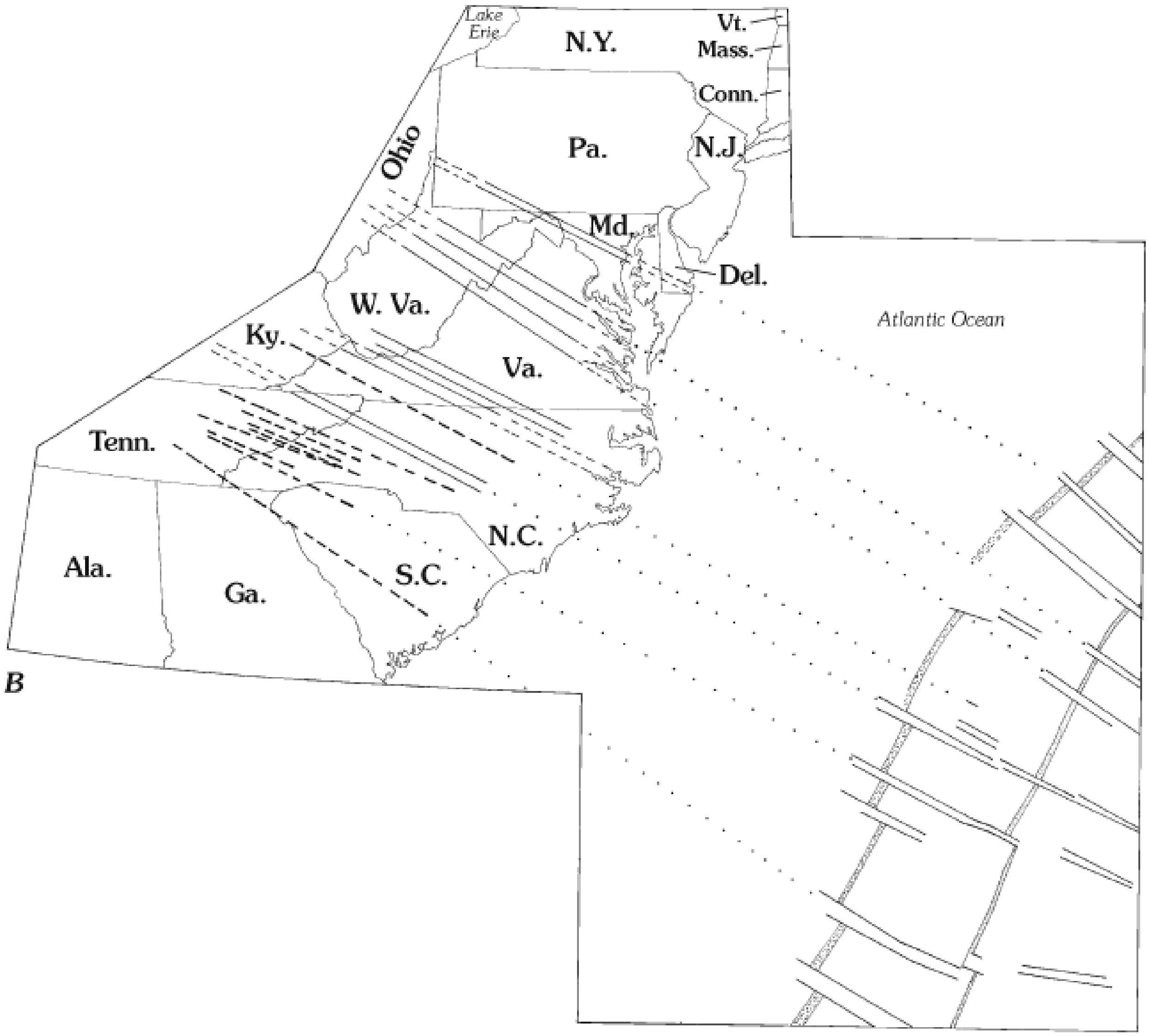



**Figure 37.** Continued.

The most conspicuous features on the images are zones in which folds change wavelength or orientation or plunge out along their strikes. These zones persist from the northern foothills through the Brooks Range itself, although in the more mountainous areas, the zones of plunging folds are partly replaced by long, straight river segments. By analogy to the Appalachian fold belt, these zones probably represent areas above lateral ramps, where décollements change stratigraphic level along strike.

Approximately 5,000 mi of unmigrated, common-depth-point seismic-reflection lines were acquired between 1974 and 1980 by Tetra Tech, Inc., under contract for the National Petroleum Reserve in Alaska (NPRA) (Wilcox and others, 1988). Seismic stations were spaced approximately 0.25 mi apart, and the quality varied from very good in the northern Arctic foothills and coastal plain to very poor in the southern Arctic foothills. Several of the available compressed seismic-reflection profiles in the Brooks Range confirm the presence of lateral ramps.

The westernmost of the hypothesized lateral ramp zones differs from those located to the east in that it shows not only fold plunges and straight river segments, but also abrupt changes in the strike of fold axes and conspicuous fold interference patterns. This type of interference pattern occurs in at least two other geographic areas as seen in Landsat and SLAR images: in China and south of the Anti-Atlas Mountains of northwestern Africa. Structures in these areas probably are the result of plate collisions. A collision from the west may have contributed to the formation of the other lateral ramps in the Brooks Range.

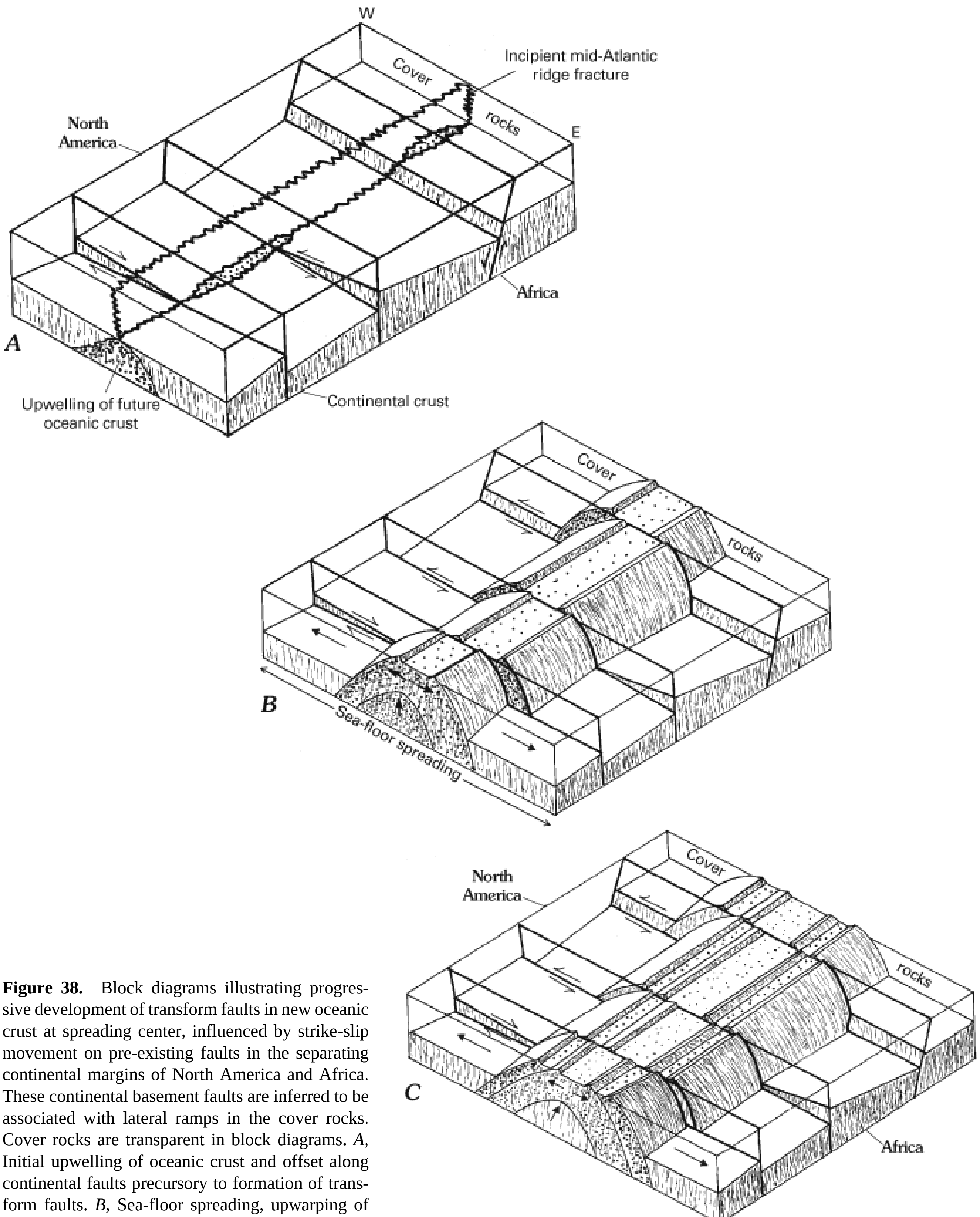



**Figure 38.** Block diagrams illustrating progressive development of transform faults in new oceanic crust at spreading center, influenced by strike-slip movement on pre-existing faults in the separating continental margins of North America and Africa. These continental basement faults are inferred to be associated with lateral ramps in the cover rocks. Cover rocks are transparent in block diagrams. *A*, Initial upwelling of oceanic crust and offset along continental faults precursory to formation of transform faults. *B*, Sea-floor spreading, upwarping of continental crust, and additional movement along continental and incipient transform faults. *C*, Additional spreading and fault movement.

Each of the easternmost three zones (fig. 39*B*) exhibits changes in fold plunge, narrowing of folds along strike, or long, straight stream segments nearly perpendicular to the tectonic transport direction. The exception is a narrow zone at approximately lat 68°45´ N., where folds show no apparent plunge along strike. This band probably represents a “null” zone similar to a zone crossing the Susquehanna lateral ramp in Pennsylvania (Montour anticline, fig. 10); the same type of zone is found on the Seven Mountains ramp in Pennsylvania (fig. 24). Fold plunges to the north and south of the null zone should trend in opposite directions. Seismic-reflection profiles and geologic maps of the area north of the null zone in the Brooks Range of Alaska (John S. Kelley, USGS, written commun., 1991) suggest that each of the easternmost hypothesized lateral ramps is up-to-the-east; geologic maps of the area south of the null zone also suggest that the ramps are up-to-the-west in the main part of the De Long Mountains.

## LATERAL RAMPS IN PAPUA NEW GUINEA

Figure 40 shows a proprietary SLAR image of Papua New Guinea near the intersection of the Papuan and Aure thrust belts. This image shows a conspicuous change in fold wavelength along strike. Coincident with this change in fold wavelength is a change in depth to basement from 30,000 ft in the east to less than 16,500 ft in the west (Ronald H. Gelnett, MARS Associates, oral commun., 1987; Davies, 1990). This abrupt change in fold wavelength is probably due to a lateral ramp at depth, although the presence of a ramp cannot be confirmed because no seismic-reflection profiles are available. As seen on the SLAR image, a line of volcanoes that occurs along this zone of abrupt change in depth to basement and a change in fold wavelength strongly suggest that the lateral ramp is underlain by a basement fracture system. Additional lateral ramps within the Papua New Guinea fold belts are illustrated in the radar images of Dekker and others (1990, figs. 11 and 12) and aerial photographs of Dow (1977, figs. 16 and 29).

## LATERAL RAMPS IN CHINA

In the late 1970’s, the USGS produced an unpublished uncontrolled Landsat mosaic of China from individual image chips (Frank Sidlauskas, USGS, oral commun., 1989). Unfortunately, the scale of the mosaic is too small to show the features discussed in this report. This mosaic shows two discrete zones in China where every fold that approaches the zone either changes width or, more commonly, plunges out (figs. 41 and 42). The northern zone is more than 1,367 mi in length, and the southern zone is more than 1,119 mi in length. Both zones are absolutely straight at the scale of the mosaicked image. Figure 42 shows a pair of individual Landsat scenes along a part of the southern zone that displays typical fold plunges indicative of lateral ramps.

# CONCLUSIONS

1. Lateral ramps are a natural part of the architecture of fold-and-thrust belts.
2. The positions of lateral ramps are indicated on SLAR and Landsat images by abrupt changes in fold wavelength, zones of plunging fold noses, and (or) long, straight river systems all across a fold belt.
3. Evidence for lateral ramps on seismic-reflection profiles may be as simple as a single along-strike fault, which rises gradually through the stratigraphic column; more commonly, the lateral ramps are multiply faulted and folded zones whose seismic signatures resemble complex dip lines.
4. Although uncommon, lateral ramps in outcrop resemble complex disturbed zones or duplexes.
5. Igneous intrusions parallel to the ramps are not uncommon and may indicate a connection to basement faults.
6. Lateral ramp zones may be associated with rapid changes in stratigraphic thickness or lithology.
7. The root zones of highly eroded lateral ramps appear to manifest themselves as lineament swarms, as seen on SLAR and Landsat images.
8. The formation of virtually all tectonic windows appears to require the presence of a lateral ramp and its intersection with a décollement or frontal ramp.
9. Disturbed zones reach a peak frequency at the margins of lateral ramps.
10. Lateral ramps appear to be connected to a Precambrian fault system that was reactivated throughout much of geologic time.
11. Seismic events common under lateral ramp zones may serve to trigger giant landslides in the Appalachians.
12. A reactivated fundamental fracture system extended offshore as the continents separated during episodes of sea-floor spreading and influenced the inception of transform faults in the new oceanic crust. This same fracture system was responsible, during earlier times of compression, for the formation of lateral ramps in the overlying cover rocks.
13. Lateral ramps are present in fold-and-thrust belts worldwide.

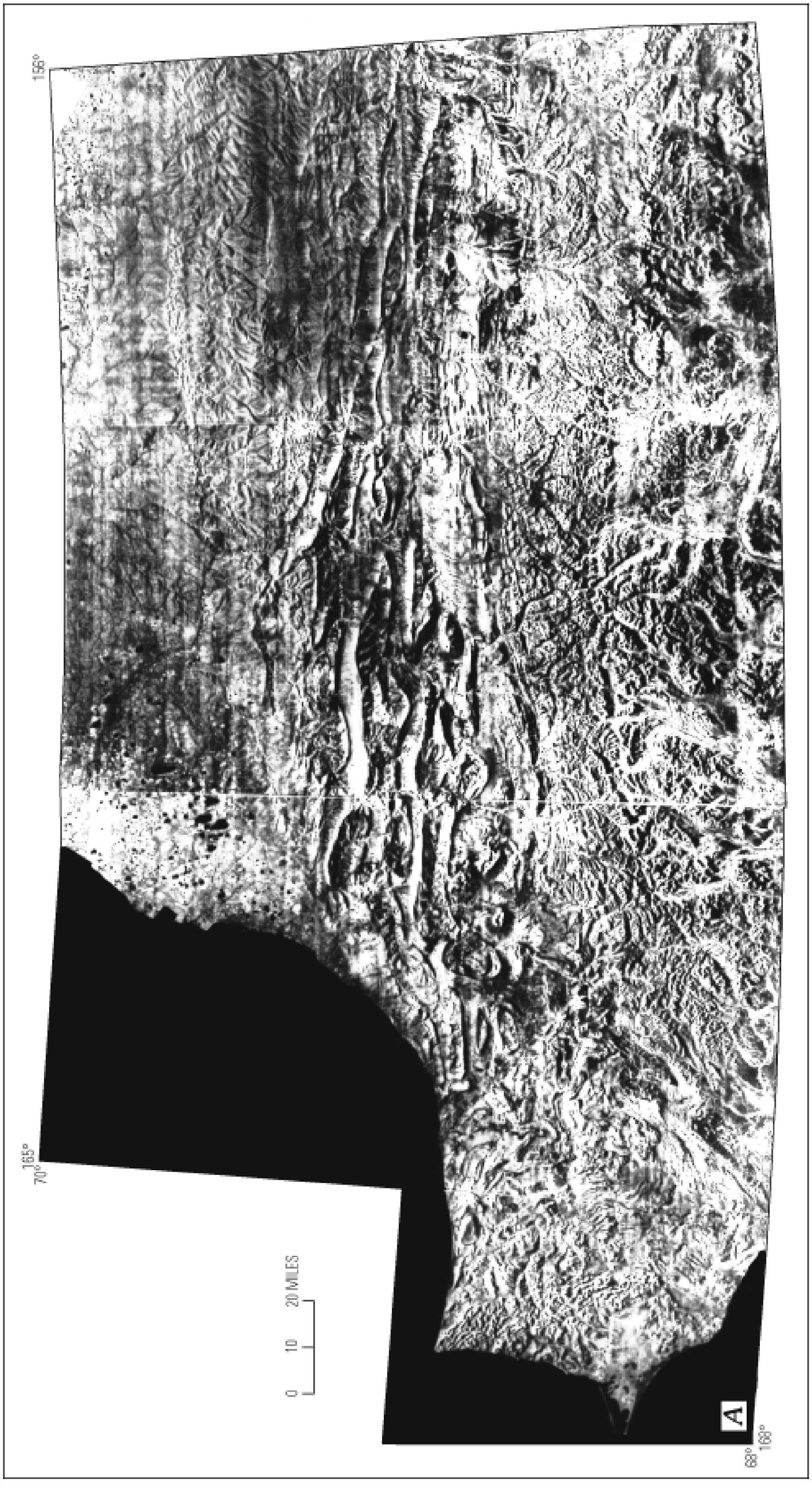



**Figure 39 (above and facing page).** *A*, Side-looking airborne radar (SLAR) image of the western Brooks Range in Alaska. *B*, Same image as *A*, showing positions of hypothesized lateral ramps.

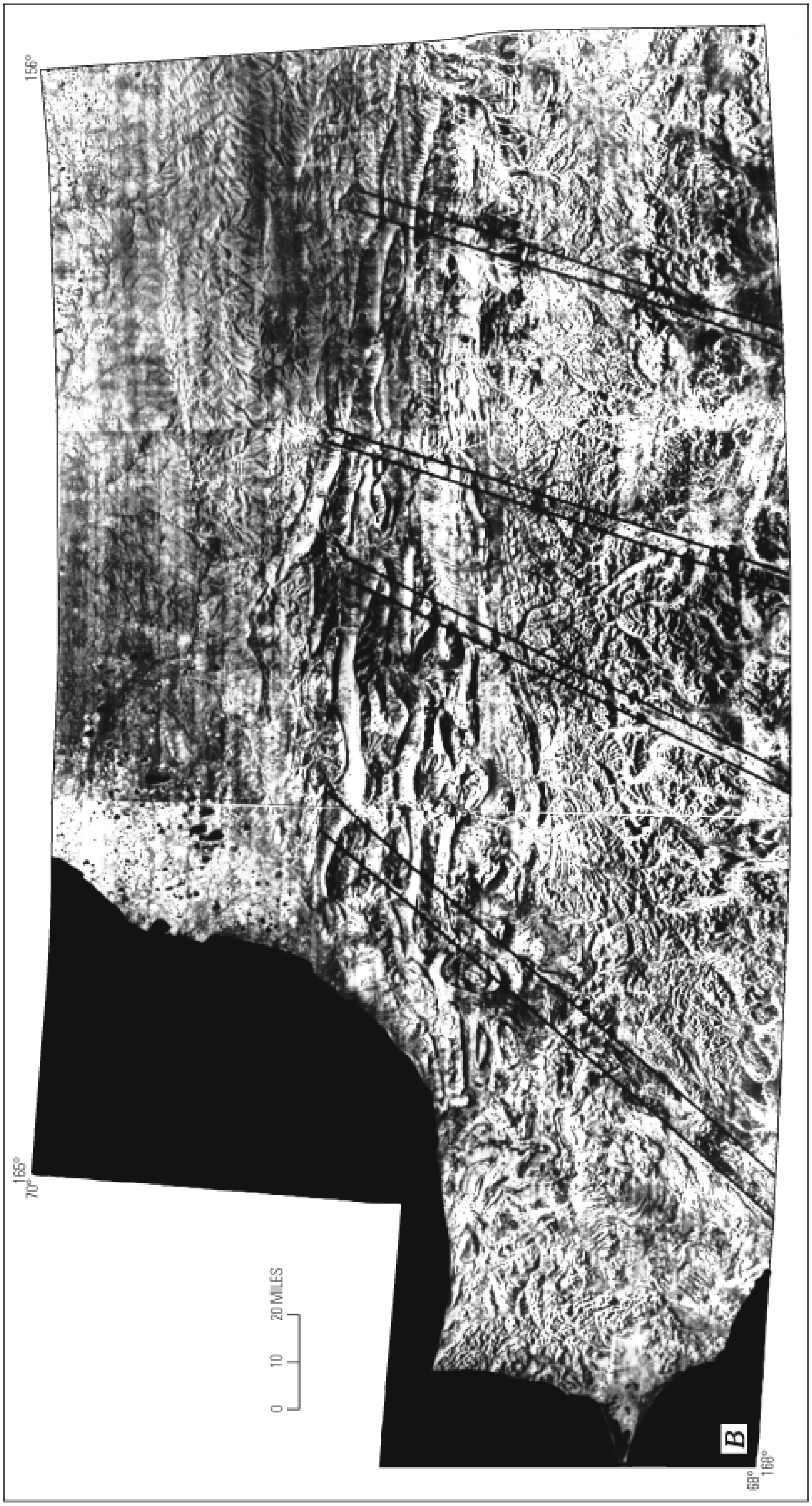



**Figure 39.** Continued.

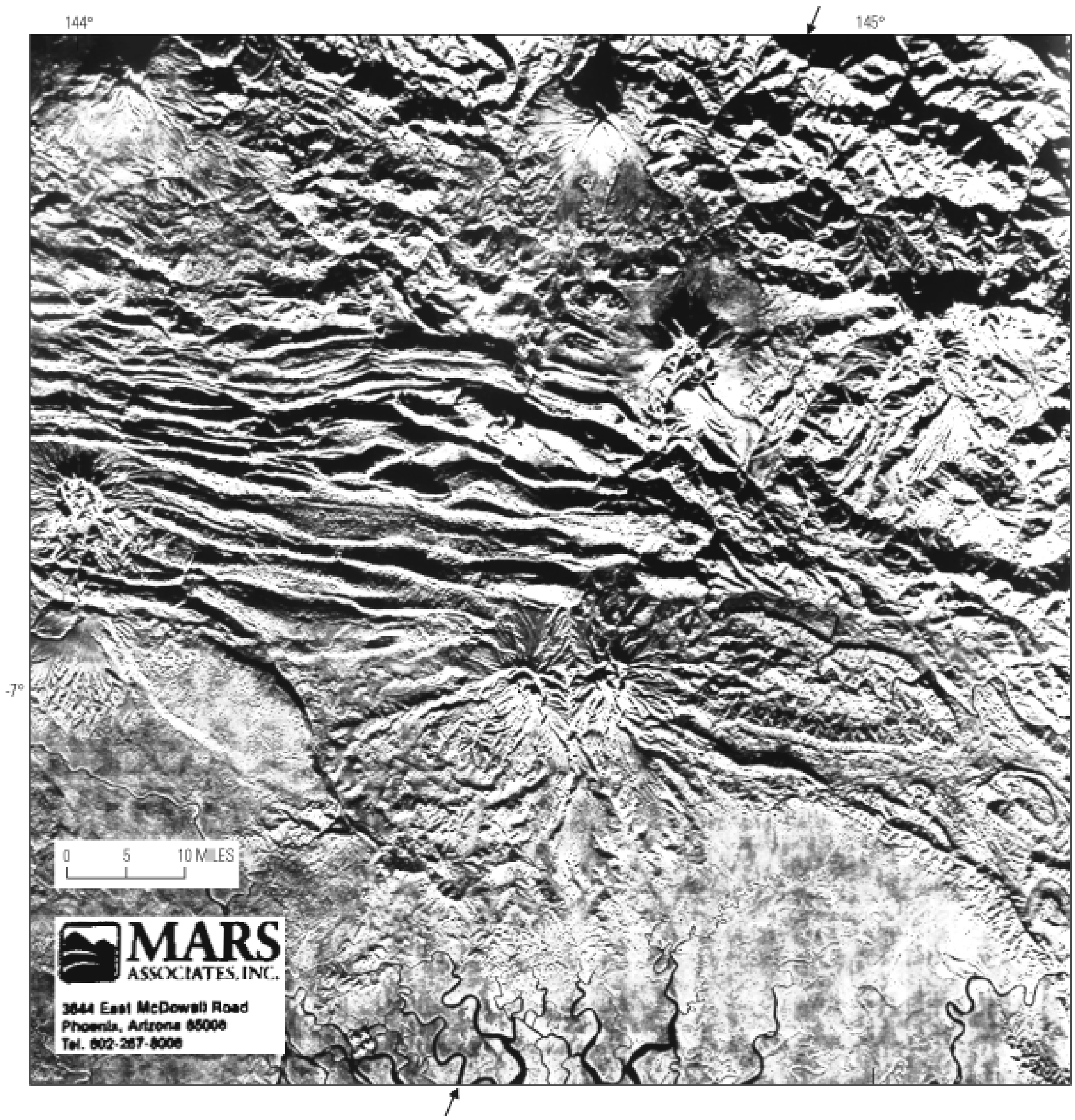



**Figure 40.** Side-looking airborne radar (SLAR) image of a part of Papua New Guinea showing change in fold wavelength along which volcanoes are aligned. Inferred lateral ramp is marked by arrows. Illumination is from south. Image courtesy of MARS Associates (Phoenix, Ariz.).

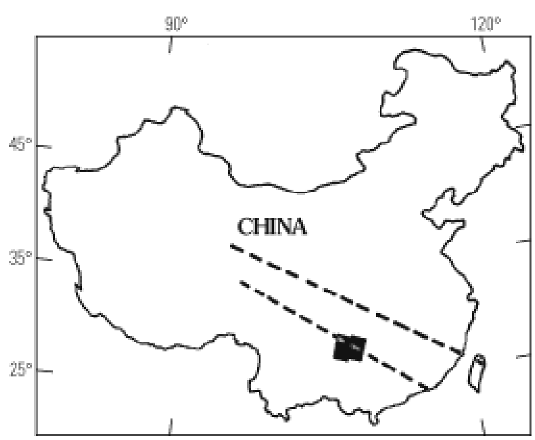



**Figure 41.** Index map of China showing the approximate location of Landsat mosaic shown in figure 42 and the two inferred lateral ramps discussed in the text.

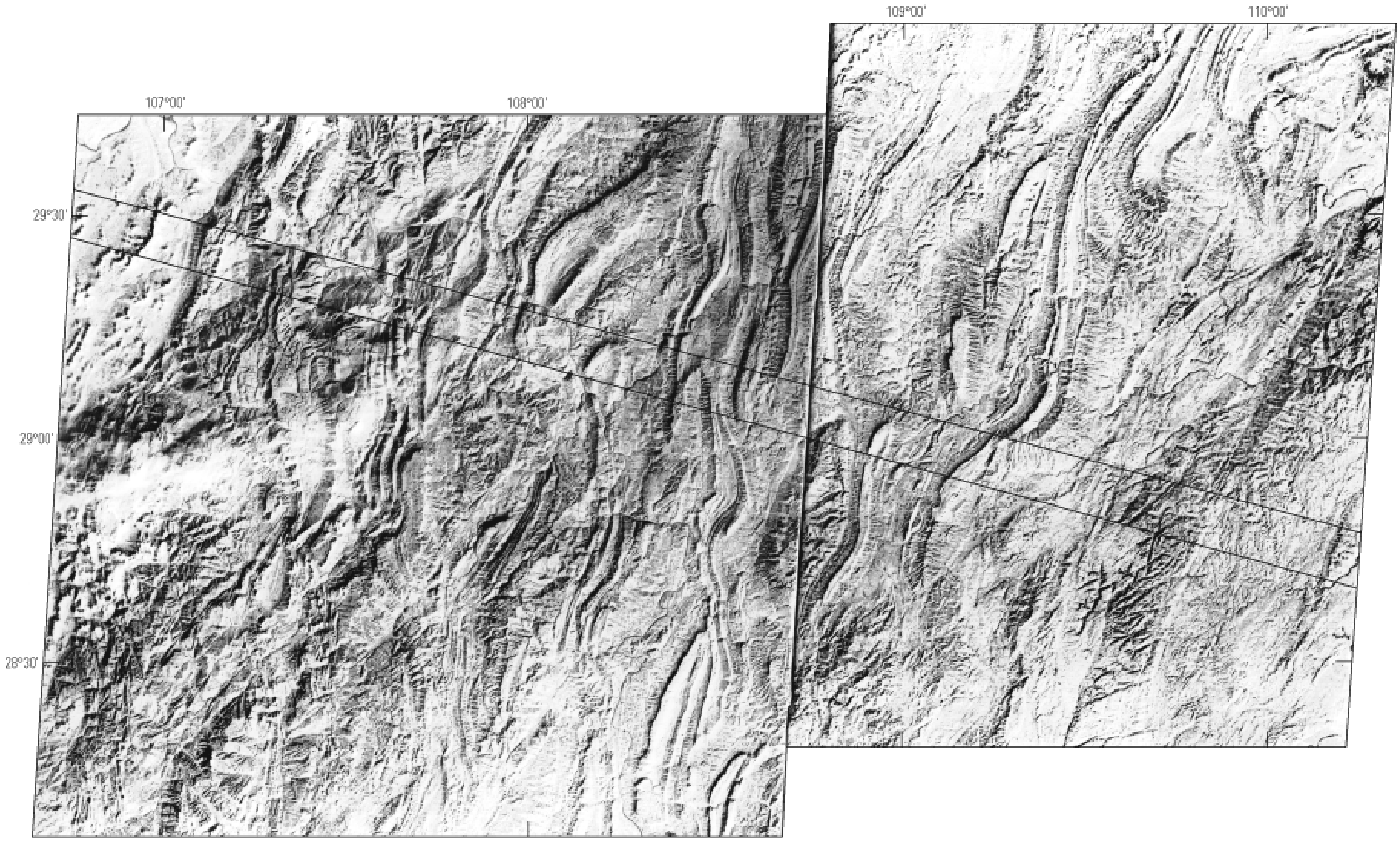



**Figure 42.** Mosaic of Landsat scenes E-1525-02475-7-01 and 1488-02424-7-01, along southern lateral ramp (indicated by parallel lines) in China (see fig. 41). Image shows an area approximately 201 mi wide.

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